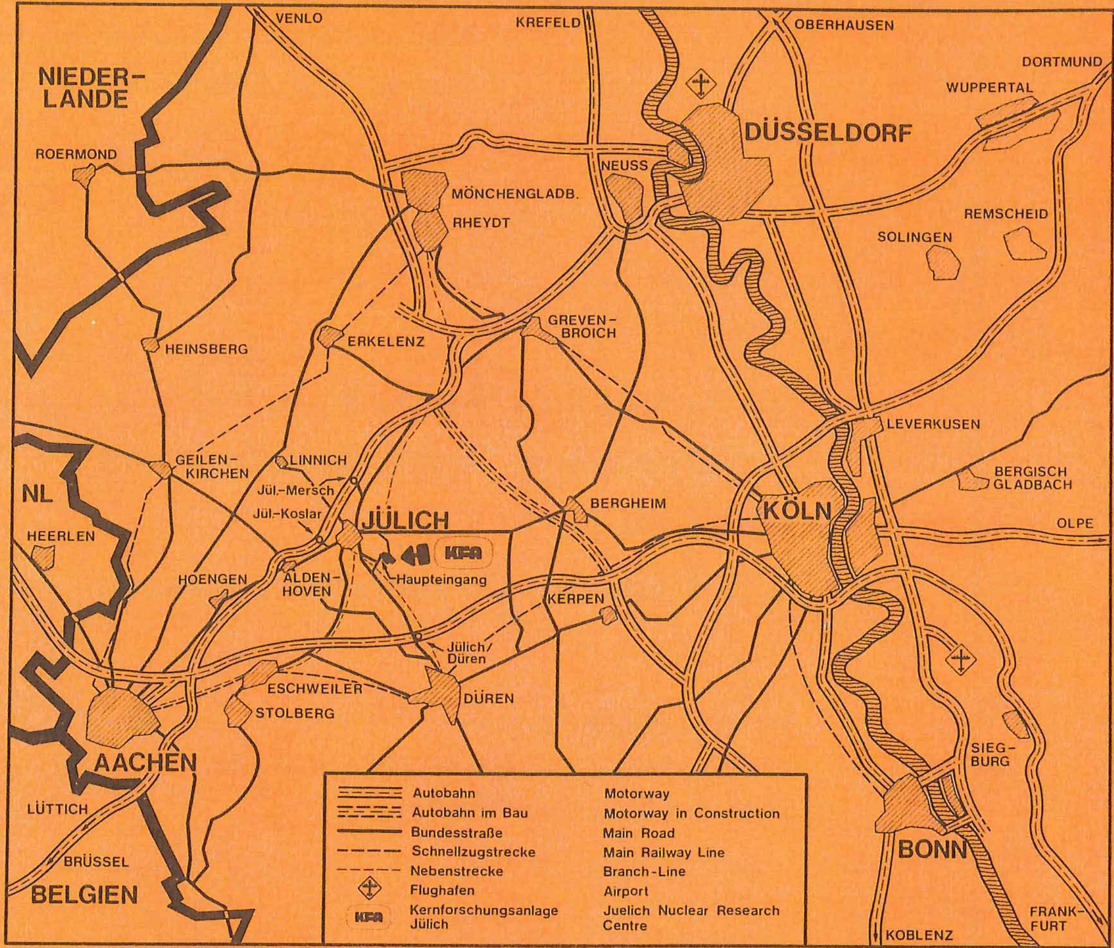
KERNFORSCHUNGSANLAGE JÜLICH GmbH
Projektleitung Energieforschung
International Energy Agency IEA

Implementing Agreement for Co-Operation in the Development of Large Scale Wind Energy Conversion Systems

Fifth Meeting of Experts-
Environmental and Safety Aspects of the present Large Scale WECS

Organised by
Project Management for Energy Research (PLE)
of the Nuclear Research Establishment Jülich (KFA)
on behalf of the
Federal Minister of Research and Technology
and The National Swedish Board for Energy
Source Development

Jül - Spez - 100
Februar 1981
ISSN 0343-7639



Als Manuskript gedruckt

Spezielle Berichte der Kernforschungsanlage Jülich - Nr. 100

Projektleitung Energieforschung Jül - Spez - 100

Zu beziehen durch: ZENTRALBIBLIOTHEK der Kernforschungsanlage Jülich GmbH

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Scientific Coordination:
E. Hau (MAN München)
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CONTENTS

LS / WECS and their influence on the natural wind field.

Rainer Roth, Hannover

I. Introduction

Most of the questions meteorologists are asked by those who are engaged in the construction and design of WECS are concerning wind characteristics. (Statistics of the wind field, problems of siting.) On the other side it may be usefull to discuse how the natural wind field is affected by LS / WECS, especially if they are grouped in farms.

II. Charateristics of LS / WECS

Here the main design data of GROWIAN are to be considered:

Height of tower	1oo m
diameter of rotor	1oo m
cut-in wind speed	6.3 m/s
cut-off wind speed	24 m/s
rated power	3 MW (12 m/s $\leq$ u $<$ 24m/s).

III. Mesoscale climatic influences

For wind speeds below 6.3 m/s the structure of such a large scale WECS will have not more influence on the natural wind field than any other tall tower. Therefore especially for situations of low wind speeds and strong inversions, which are most important for air-pollution problems, there is really no effect of LS / WECS to be discussed. The same is true for wind speeds above 24 m/s.

In the range of wind speeds between 6.3 and 24 m/s the WECS will convert kinetic energy into electric energy. By this the wind speed in its wake is lowered. But in those parts of thhe country, suitable for LS / WECS _ installation, higher wind speeds are considered as a disadvantage. There people make use of shelter effect of hedges and tree rows. Even by the use of well designed WECS - farms there is no danger of changing the windclimate to a degree that is uncomfortable, because they will be spaced so, that they are exposed allto gether to high windspeeds, that is at rather large distances.

Further on even in the center of the wake close to the LS / WECS the wind speed is only lowered to one thirds of the value in front of the LS / WECS. Therefore in all cases enough ventilation for the country-side behind WECS is left.

If LS / WECS are used in a larger number in coastal areas the effect of roughness- change between sea and land will be increased, so during those periods when the wind is blowing from the sea there will be an increase in precipitation and in cloudyness. But fore the time being, it is not possible to give a quantitative figure of that influence. Both effects are due to the convergence of the wind in front of an area with increasing surface roughness. Effects like this are also observed in the vicinity of larger cities, partly for the same reason, partly for thermodynamic reasons.

IV. Kinetic energy in the atmosphere

A sa climatological worldwide figure the kinetic energy of the global atmosphere is

$$E_k = 1o^6 \ J/m^2$$

with a rate of production of

$$P_k = 2 - 5 \ W/m^2 .$$

This rate of production is balanced by an equal rate of dissipation. Usually it is assumed that half of this dissipation occurs in the planetary boundary layer.

The rate of production of kinetic energy can be compared with the total amount of energy entering the atmosphere. The latter quantity is measured by the solar constant which is the amount of energy recieved per unit area and per unit time at the outer limit of the atmosphere. It is normally given as

$$S_o = 1.354 \text{ kW/m}^2 .$$

The total amount intercepted by the atmosphere is $S_o \quad a^2$ where a is the radius of the earth. Since the total area of the earth is $4 \quad a^2$ we find that the energy recieved from the sun at the outer limit of fhe atmosphere and measured per unit area of the surface of the earth is

$$1/4 \; S_o = 338 \text{ W/m}^2 .$$

A good part of this energy is reflected back to space without entering the atmosphere. Taking the atmospheric albedo to be, 32% there will be 68% which enters the atmosphere, or 23o W/m^2. Considering the energy conversion rates by looking at the dissipation rates given above we find that the efficiency of the atmosphere as an engine is 1-2%.

Since dissipation of kinetic enrgy means transformation into heat, WECS transformating kinetic energy into electrical energy have to work in competition to the natural dissipation rate and they can only make use of part of that energy if they are used on a larger area.

V. The planetary boundary layer

The planetary boundary layer is a special type of flow. Over land its height is about 1oom during the night and about 6oom during daytime, which is typical for fine weather, while during strong winds and/or day with much cloudiness the variation in height is smaller. The height of the planetary boundary layer also is smaller over relativly smooth terrain (sea) than over rough terrain. For the same surface conditions and a given thermal stratification the heigt is growing with increasing wind speed.

If we use for a first order approximation the logarithmic wind profile than the dissipation of kinetic energy ε in the planetary boundary layer per unit of surface area is given by

$$\varepsilon \simeq \int_{z_0}^{H} \rho \frac{u_*^3}{\varkappa z} dz$$

where is

ρ the density of air (ρ = 1.25 kg/m^3)

u_* the shearing stress velocity

($u_* = \sqrt{\frac{|\tau|}{\rho}}$)

τ the vertical momentum flux

z_o the roughness length

(z_o = o.5 m for northern GErmany)

H height, below which most of the energy dissipation in the boundary layer occurs

(H = 1oom assumed).

The shearing stress velocity may be calculated by use of the resistance law of the planetary boundary layer. In dependency of the wind speed on top of the boundary layer (geostrophic wind speed) and with a assumed geographic latitude of about 5o^o one gets the following table for the shearing stress velocity, the dissipation rate and the wind speed at a height of 1oom.

u_{geo}	5	1o	15	2o	25	3o	m/s
u_*	o.25	o.45	o.64	o.84	1.oo	1.18	m/s
ε	o.25	1.5	4.3	1o	16.5	25.4	W/m^2
u_{1oom}	3.3	6.o	8.5	11.2	13.2	15.5	m/s

Those figures are valid for neutral thermal stratification. For geostrophic wind speeds smaller than about 15 m/s we would get get smaller values of the dissipation rate and the velocities for a stable boundary layer and larger values for an unstable boundary layer.

If we use as a rough guess the assumption that 1o% of the natural dissipation can be converted by a farm of LS / WECS than the area F can be calculated which has to be reserved for each GROWIAN of that farm.

u_{1oom}	6.3	8	1o	12	15	m/s
P_G	o	o.75	1.6	3	3	MW
ε	1.8	3.5	6.9	12	24	MW/km^2
F	o	2.1	2.3	2.5	1.2	km^2

Here P_G is the output of GROWIAN. The maximum area is needed at 12 m/s giving a maximum distance between each WECS of about 1.6 km or 16 times the rotordiameter. This is equivalent to λ =o.oo3 for the relation of rotor area to surface area.

This result depends linearly an the assumption that 1o% of the natural dissipation could be used by each GROWIAN. Since the space for one WECS depends also on the windspeed the result depends on the windstatistics of the site. Furtheron, the situation is less favorable during nighttime but better during daytime. Under off-shore conditions, where windspeeds are higher due to a smaller surface friction, the natural downward flux of energy is smaller so that LS / WECS would have to be spaced at larger distances.

At about 5% of all the nights of the year very strong inversions occure together with wind speeds at 1oom height of about 1o m/s. Under this conditions the height of the friction layer is sometimes less than 1oom, so that the WECS would operate partly outside the friction layer. Than the renewal of kinetic energy within the wake of the WECS may depend on the action of the pressure gradient force, which will take hours to accelerate the air in the wake again. Even the turbulence generated by the WECS will be damped out very fast under those conditions.

Other than in windtunnel modeling, where the flow is in the direction from higher pressure towards lower pressure, so that the wake may be accelerated by the pressure force in the right direction, flow in the atmosphere is about parallel to the isobars and the pressure gradient is very small ($\frac{\partial p}{\partial n} = \frac{1\,\text{mbar}}{100\,\text{km}}$ for u_{geo} = 1o m/s).

VI Final remarks

There are still a lot of open questions. Some of those will be answerde by further theoretical work, others may depend on emperical investigations when LS / WECS are in operation. Experimental work in windtunnels may contribute as well, but since the planetary boundary layer is a special typ of flow, those results may differ from results gained in the real atmosphere.

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Staffan Engström,hj

EXPERIENCES FROM SITING TWO LARGE SCALE WECS PROTOTYPES IN SWEDEN

Staffan Engström, Program Manager, National Swedish Board for Energy Source Development.

To be presented at the IEA Large Scale WECS meeting in Munich September 26, 1980

ABSTRACT

The wind energy program of the National Swedish Board for Energy Source Development (NE) is dominated by the two large scale WECS that will be built at Näsudden on the island of Gotland and at Maglarp in the province of Skåne in southern Sweden. The paper covers the experiences encountered when NE's operating agents applied for permission to site the power plants. The general attitude of authorities and people in general was fairly positive, however some differences in attitude at the two places could be recognized. The experiences are specific for Sweden, but some general conclusions can be made.

1. Background

The wind energy program of the National Swedish Board for Energy Source Development (NE) is dominated by the two large WECS prototypes which were ordered from Karlskronavarvet AB and KaMeWa AB respectively in mid-1979. The units will be erected with the Vattenfall and Sydkraft utilities acting as operating agents for NE.

The Karlskronavarvet WTS-3 unit (see figure 1) holds a 78 m diameter teetering hub turbine on a 80 m steel shell tower. The generator (synchronous) is 3 MW. Blades will be wound of glass-fibre reinforced epoxy. Karlskronavarvet cooperates with Hamilton Standard, USA. The WTS-3 is in most aspects identical to the WTS-4 being delivered to Medicine Bow, Wyoming, USA.

The KaMeWa unit (fig 2) consist of a 75 m diameter stiff hub turbine on a 75 m concrete tower. The generator (induction) is 2 MW. The blades are made of welded and bolted steel with some shape elements of GRP. KaMeWa, formerly known as Karlstads Mekaniska Werkstad or KMW, cooperates with the ERNO company of Western Germany.

The first rotation of the units will occur in the 1981-82 period. An extensive testing and evaluation program will be carried out to form the basis for a planned long range Parliamentary decision in 1985 on the use of wind power in Sweden. Possibly one or more demonstration group (5-10 units) might be planned within the period. (Fig 3).

The installation to be sited includes, besides the WECS prototype, a meteorological mast and an information building with facilities for visitors. (Fig 4).

2. General description of the areas

The areas chosen - South Skåne and South West Gotland - were selected mainly due to the good availability of wind energy. (Fig 5). The median wind speeds in these areas (around 8 m/s at 100 m height) are the best for land areas in Sweden. The land is open, flat and with little vegetation except for grass and crops. The areas are part of the normal distribution regions for Sydkraft and Vattenfall respectively.

The Karlskronavarvet unit will be built at Maglarp in the southernmost region of the province of Skåne in South Sweden (fig 6). This is a heavily populated wealthy farm area containing some of the best farmland in Europe. However, the wind power plant site has a medium classification from a soil condition standpoint.

Since the site is situated close to the seashore (2 km), and due to the strategic situation of Skåne, special considerations had to be given to the military.

The electrical grid is strong in the south and southwest parts of Skåne.

The island of Gotland in the Baltic is also a farm area, although very different from Skåne.

The soil conditions are often very bad, with sparse grass for sheep grazing as the only possible means of utilization in many areas (fig 7).

The island (3 170 km^2) has only about 50 000 inhabitants.

For many years the population was slightly declining due to the diminishing demand for labour in agriculture, but after the establishment of some industries in the island "capital" of Visby, and an extension of the cement industry, the population seems to have stabilized.

The electrical grid is fairly weak on Gotland. The main energy production is by large (12 and 19 MW) diesels, some of them used for waste heat utilization for district heating of Visby. There is an old 28 MW direct current cable connection with the mainland of Sweden. Shortly after the nuclear referendum last spring, however, it was decided to build a 130 MW cable link. Thus Gotland to a great extent will be integrated electrically with the rest of Sweden, which will make it possible to build comparatively large installations of wind power in the future.

Another important societal factor is that there is a wind power tradition on Gotland. Many people have first-hand experience in handling small wind generators for electricity production. There is a large number of traditional wind mills and many are still kept in good state.

The tourist industry is also important to Gotland.

3. The siting procedure

The siting procedure started in February 1978 with the first meeting of the specially formed "NE Committee for siting of WECS prototypes". This group consisted of a chairman representing NE, one member from each of the utilities and members from the county administrations (länsstyrelsen) of Malmöhus county or "län" (includes southwest Skåne), Gotlands län and Uppsala län. The research WECS of Kalkugnen, Älvkarleby, is situated within the county of Uppsala län. Since NE originally planned three prototype WECS three main areas were chosen. After some time it became apparent that the government would not approve the construction of more than two prototypes. Being the least windy area, the "Uppsala län site" was thereafter looked upon only as a spare site. It will not be discussed any further in the paper.

In Sweden there is a difference between the procedures for obtaining building permits, etc that apply to government authorities as compared to others such as private companies and individuals. A government authority is expected to fulfill some of the internal control functions that would otherwise have been executed by the ordinary regulating authorities. NE is of cource an authority, as is the Vattenfall (State Power Board). It appeared essential, however, to apply the normal application procedures in at least one case. Thus it was decided to let Sydkraft (formally a private utility company), act in its normal roll despite the fact that it is an operating agent for NE.

The work started with a re-examination of the wind data and the siting criteria developed for the 1977 NE siting study (ref. 1, 2). As representatives from the county administrations were included in the group realistic alternatives for the exact siting could be selected after informal discussions. This meant that no efforts had to be wasted on alternatives that the county and other administrations would not approve. The scheme seems to have satisfied both parties.

3.1 Skåne

The governor (landshövdingen) and head officials of Malmöhus län were informed in April 1978.

The same month informal discussions with the following divisions of the Malmöhus län county administration took place:

nature conservancy (naturvårdsenheten)

planning (planenheten)

law (juridiska enheten)

defence (försvarenheten, militärassistenten)

regional economics (regional-ekonomiska enheten)

historical monuments (länsantikvarien)

By the same time informal contacts with the road administration (Vägverket), the telecommunications administration (Televerket) and the military (Militärbefälhavaren) took place. Within Sydkraft the possibilities of connecting the WECS prototype with the grid at various sites were investigated, as well as the possibilities of arranging the road transportation of heavy and bulky items. Foundation conditions were also examined briefly.

By May of 1978 five possible sites remained (Klagshamn, Maglarp, Larsboda, Östra Klagstorp and Dybäck). A harsh comment from the powerful farmers´ organisation LRF resulted in a meeting in June between the board of the LRF county section and NE-Sydkraft. LRF generally defends "the good earth" against any other use than for farmland. The meeting ended in peace concerning the single prototype, and LRF made clear that its comments were rather meant for extensive use of WECS. The land use for a serial WECS including grid connection and accessroad is estimated at a modest 3 400 m^2, the same as the gross consumption for two one-family houses.

In September 1978 official information about the alternatives was dispersed to the board of the county administration, the five municipalities (kommun) involved and to the local sections of the LRF. No objections were raised against the single prototype, but scepticism about multiple installations remained. Some of the municipalities even welcomed a prototype WECS. Following this official information the remaining local landowners were contacted. The public was informed at a public meeting arranged in collaboration with LRF.

In a meeting with the military at one of the possible sites in October 1978, the military concluded that even if a WECS prototype might present some immediate problems, this process would be rather useful as it would help them to learn how to handle possible future large installations.

Original plans called for wind measurements using mobile meteorological masts of 40-50 m height. Time and other considerations indicated, however, that an alternative method using pilot baloon measurements was more feasible. Sodar was also used to some extent for stability measurements. Measurements were performed during the fall of 1978. Comparisons were made with normal wind measurements in nearby masts. The methods used have been reported within the IEA R&D agreement. The evaluation that was presented for the siting group in January 1979 revealed that there were no significant differences in wind speed at hub height between the different alternative sites or when moving from the coast 5 km inland. The accuracy of the method was estimated at + 0,3 m/s in relative order.

The January meeting of the siting group concluded in priority recommendations for Skåne (Maglarp) and Gotland. In March the NE board decided to follow the recommendations, but the decision was not made public until negotiations with the relevant landowners had been completed in May. At the same time the municipality and the board of the county administration were informed. A public information meeting was held. Formal applications were sent to the county administration and the military commander (militärbefälhavaren). The war protection board (krigsskyddsnämnden) was notified because it decides on war protection measures for large electricity production facilities.

By this time complains came from the local aeroclub operating the small airfield close to Maglarp. They had just decided to rearrange the grass "runway" to a direction in conflict with the planned WECS. In February 1979 the Civil Aviation Board (Luftfartsverket) concluded that the installations would not affect operations at the airfield. An exemption from the formal obstacle clearance requirements was only needed for the met mast.

In April 1979 representatives from NE, Sydkraft and Vattenfall met Civil Aviation Board and Air Force officials. NE proposed a rotating sodium light beacon (one flash per 3 s) on the nacelle besides the standard obstruction lights on the nacelle and the met mast. The rotating beacon should tell airmen about the special character of the obstruction, e.g. the rotating blades. The CAB and Air Force insisted, however, on having lights in the tips of the blades, to be lit at least on the top of the trajectory. This would mean about one flash per second. The solution could be acceptable from an estetic point of view - permanent lights on the rotating blades might otherwise give the WECS a surely not wanted impression of an amusement park - but it appeared that there were no lamps available that could withstand the 30 G acceleration for more than a short time. NE and the utilities feared of cource the problems of frequent changes of lamps. The aviation people accepted the explanation but called for painting the outer third of the blades in red - white and installing high intensive lights on the top of the met mast. The problem was settled for the prototypes in August 1980.

During the negotiations one landowner suddenly withdrew. He was in no way negative to the WECS prototype, but rather the problem was that taxes would reduce the income from the sale to such an extent that he was no longer interested. The problem was solved by moving the WECS prototype site a short distance to a plot owned by another landowner who was willing to sell. It might have been possible to force the first landowner to sell the land by a legal procedure, but this might have taken years and certainly would not make the WECS "a good neighbour". In future similar cases it can be advisable to lease land instead of buying.

Due to the time needed for the county administration to approve the project, the building permit had to be devided into three separate approvals: met mast, information building and WECS prototype including a control building.

In June 1979 the planning board (byggnadsnämnden) at the Trelleborg municipality declared that it would not oppose erecting a WECS prototype at Maglarp. At the same time the county administration gave final permits to erect the 120 m meteorological mast. According to the Skåne county member of the siting group, the county administration had decided to approve the whole installation, provided that the county antiquarian could influence the appearance of the exterior of the planned information building. This influence resulted in several rejected designs. The final approval of the project according to the Nature Conservancy Law (Naturvårdslagen) was obtained in April of 1980.

Trelleborg municipality formally approved the project shortly afterwards, on May 13. The prefabricated information building was erected just in time for the opening of the exhibition in June 1980. About 25 visitors a day visited the site last summer.

In late June 1979 the government approved the NE decision to choose Karlskronavarvet as the contractor for the Maglarp unit.

The met mast was installed during the summer of 1979. In October 1979 routine measurements started. Turbulence measurements will take place in campains and might serve as a final check-point of the technical assumptions for the design.

During the fall the grid connection of the WECS was decided. Due to the sensitive landscape - and partly to large number of geese which frequent the area - the last kilometer of the 50 kV power line had to be drawn as an underground cable.

The construction work for the prototype itself started at the site on September 15, 1980. First rotation is expected in November 1981.

3.2 Gotland

Most of the siting work on Gotland followed the same scheme as in Skåne, but there were some important differences. On Gotland, the county and the municipality comprise the same area, which favours a close cooperation, as does the fact that Gotland is a small place, at least as far as the number of inhabitants is concerned. This makes a "everybody knows everything" situation in a way different from Skåne. The Vattenfall role of a government authority in some cases means that it simply informs about its intentions instead of asking for permits.

The governor of Gotland was well informed about the project. Indeed, he had acted since 1976 to make the island "a testing ground for wind power" and at an early stage got ministers to put this on paper.

Possible sites were investigated by car in May 1978. Besides the already known Ygne site close to Visby, three more sites were identified. During discussions at a joint meeting with the county administration and the municipality in September, the number of sites was reduced to two. The Ygne site might be used for a single installation, but since the area was planned for urbanization, it was not suitable for a group. Thus it was not recommendable according to the municipality officials. Another site was descarded for nature conservancy reasons. The remaining two - Eksta and Näsudden - looked promising.

The people at Näsudden even had asked for the prototype, according to a county official. This desolate area with a diminishing population wanted to get job opportunities, out of the wind.

The pilot baloon wind measurements during the fall of 1978 demonstrated that Näsudden was the best alternative. It was therefore recommended by the siting group at their January 1979 meeting.

In February 1979 an information meeting was arranged for the people living in the Näsudden area. The governor opened the meeting. The attitude was still positive, but the possibility of getting a compensation arose: the last 7 km of the road to the point of land called Näsudden was narrow and in a bad state. This problem engaged both the governor and the director general of the Swedish road administration (Vägverket) before it was finally settled to the benefit of the people at Näsudden. Questions arose as to possible tv-interference and noise but not in respect to landscape intrusion or birds. Later in the spring a public meeting was arranged, preceded by a brochure that was distributed to all Gotland households.

Generally the attitude of the Gotland officials is very positive and helpful. The county antiquarian (länsantikvarien) for example, is actively engaged in working for the introduction of wind power. Gotland's Historical Museum which normally displays a permanent antique exhibition arranged a special wind power exhibition. The planning board insists that the information building and permanent exhibition at the prototype site shall open in May 1981. At least three parties are interested in leasing the rights for a coffee shop in the building. For the moment a coffee shop is not being planned since health care regulations make it economically unfeasible due to the installations needed. The tourist organization supports the plans for the WECS prototype because it will give the island yet another excursion point.

The planning department of the county administration had very precise ideas about what sort of building that would suit the landscape. Since Vattenfall had engaged their own architect in this project, it was easy to make the drawings accordingly. There has not been any objection to the prototype design so far.

The main landowner (the church) demonstrated its willingness to support the project from the beginning. The met mast is erected on land leased from a farmer who is now engaged for the supervision of the site. The local LRF district also supports the project. The military have raised no objections.

The government finally approved the NE decision to choose KaMeWa as contractor in September 1979. The construction at the site will start during the winter of 1980/81 and first rotation is expected in May 1982.

Achnowledgements:

Mr Bertil Olsson, Sydkraft, and Mr Gunnar Grusell, Vattenfall, who managed the siting work within their respective utilities, have contributed valuable first-hand impressions from their siting experiences. Mr Sven Hugosson, AIB, who acted as chairman in the siting group, contributed with his experiences. Mr Stig Wigstrand, Teleplan, provided crucial assistenace in compiling the information.

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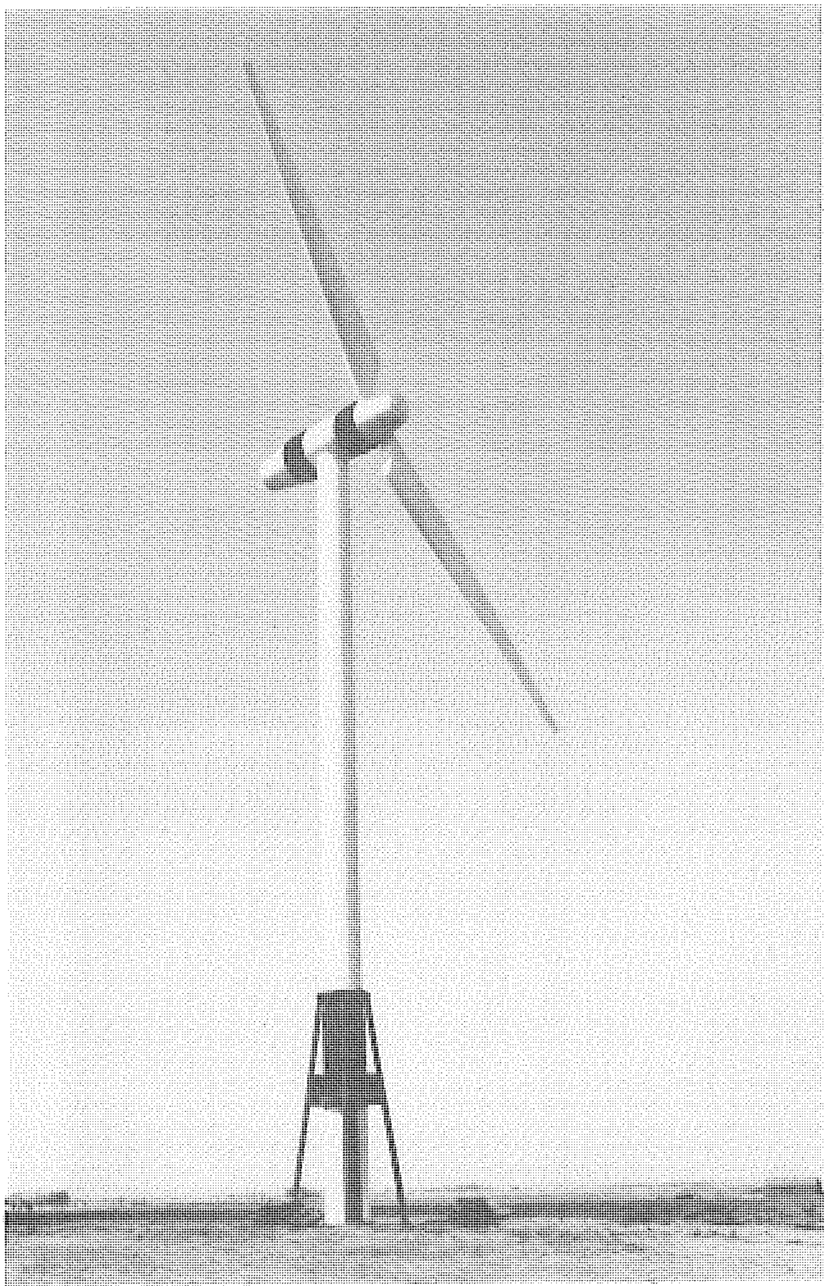


Fig 1. A model of the Karlskronavarvet WTS-3 WECS prototype at the Maglarp site.

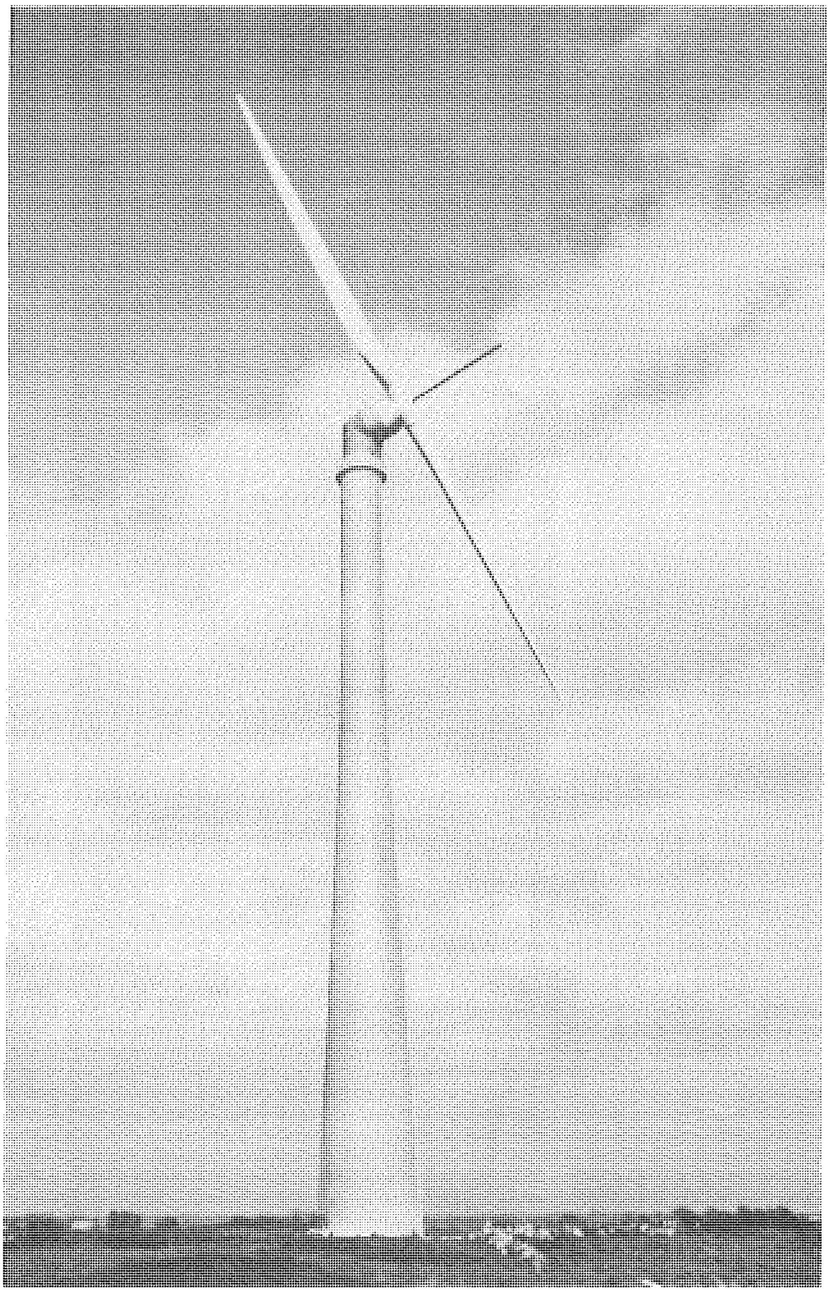


Fig 2. A model of the KaMeWa WECS prototype at the Näsudden site.

Fig 3.

A potential wind power group consisting of ten KaMeWa 2 MW WECS. Energy production 65 million kWh per year when sited on Gotland. The distance to the nearest WECS is 600 m and to the farthest 4 000 m. The individual units are placed 500 - 1 000 m apart.

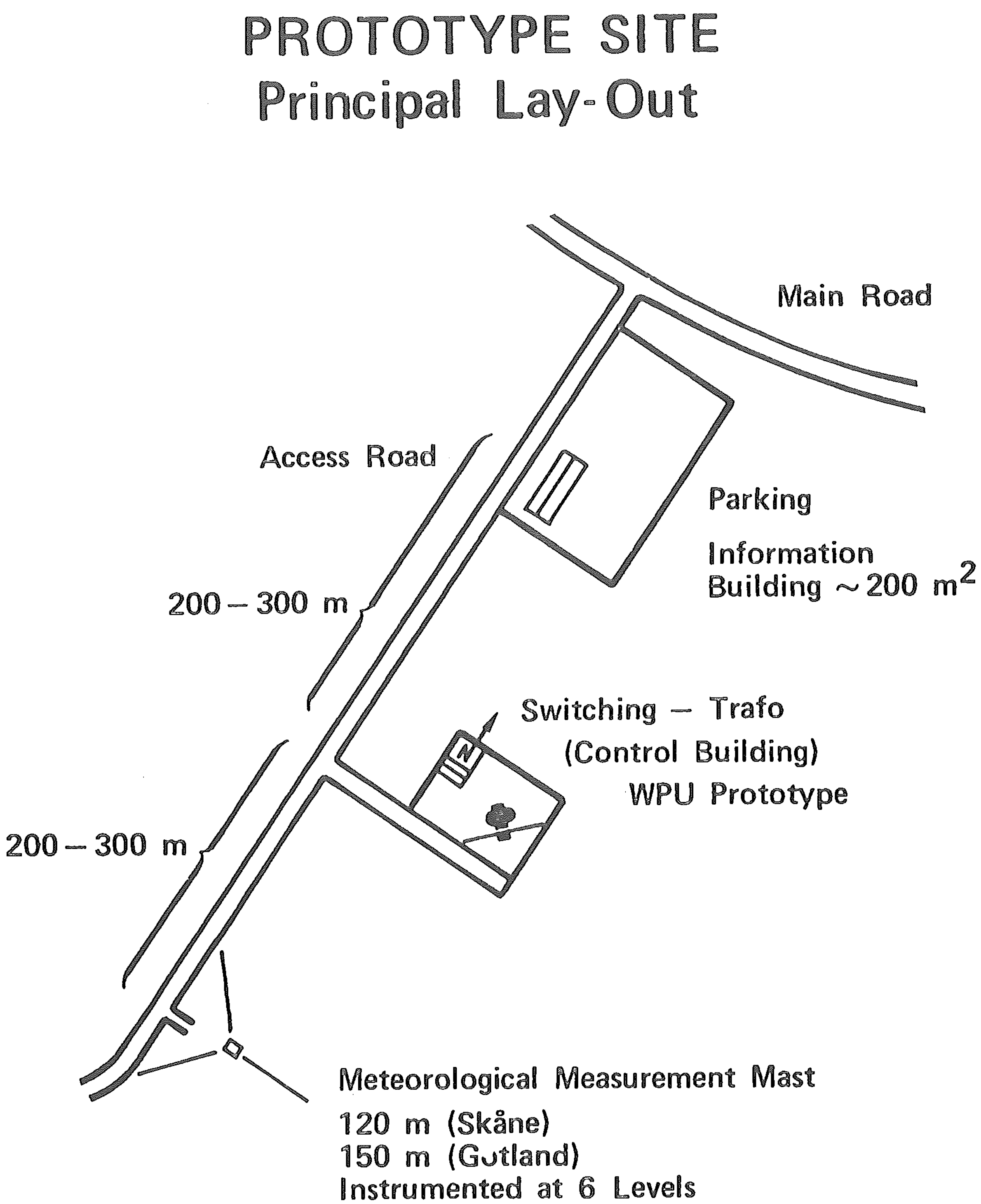


Fig 4. The principal lay-out for the prototype sites.

PROTOTYPE SITING

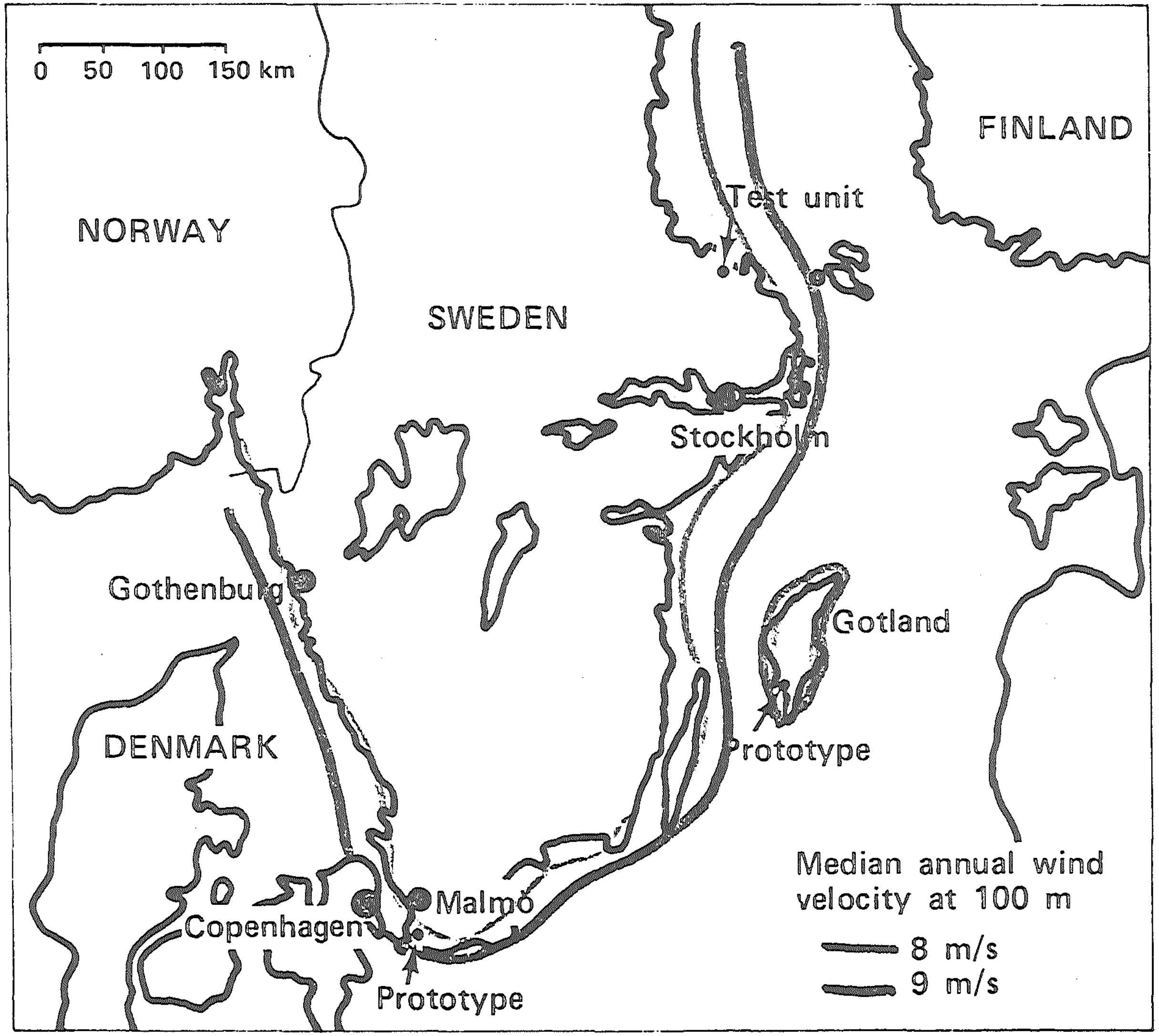


Fig 5. The location of the WECS prototypes in relation to windy areas i Sweden.

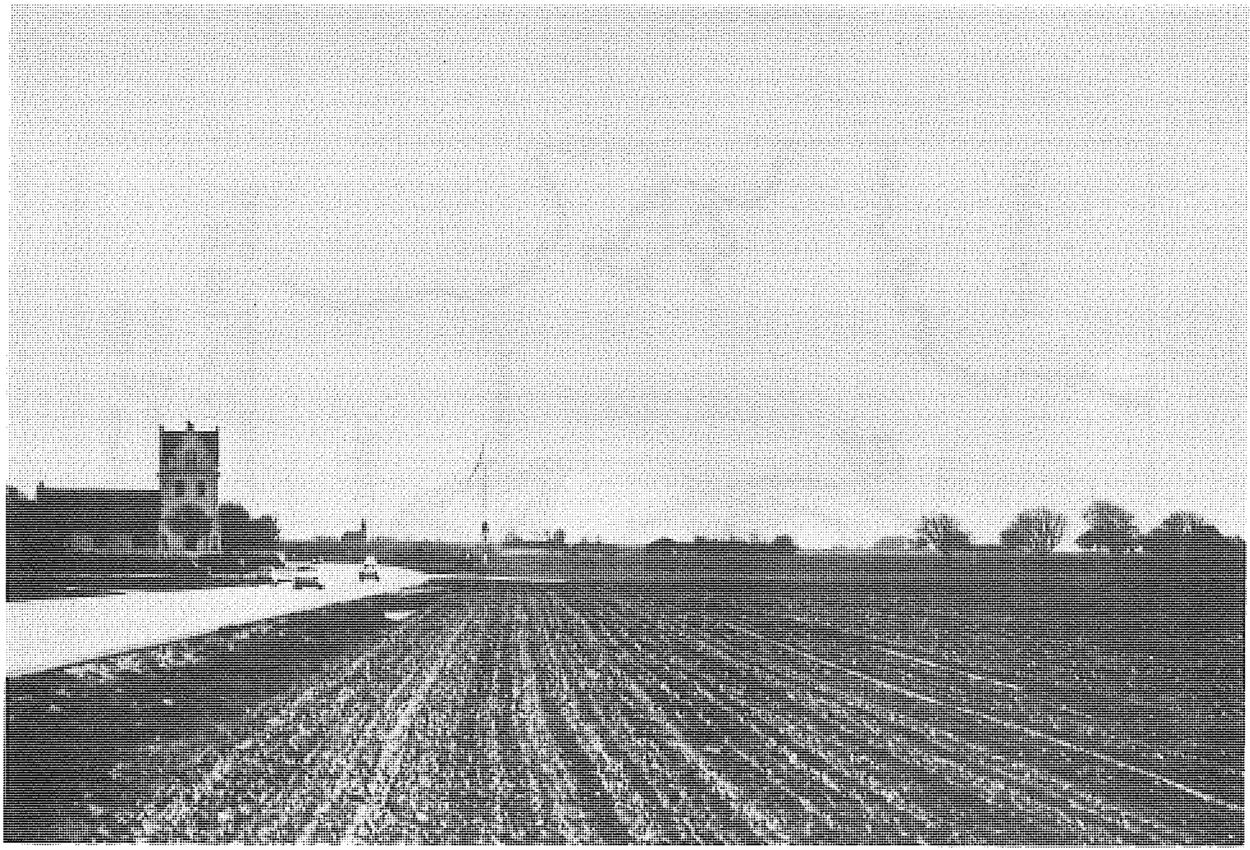


Fig 6. A photo montage of the Karlskronavarvet WTS-3 at the Maglarp site. Distance 2 km.

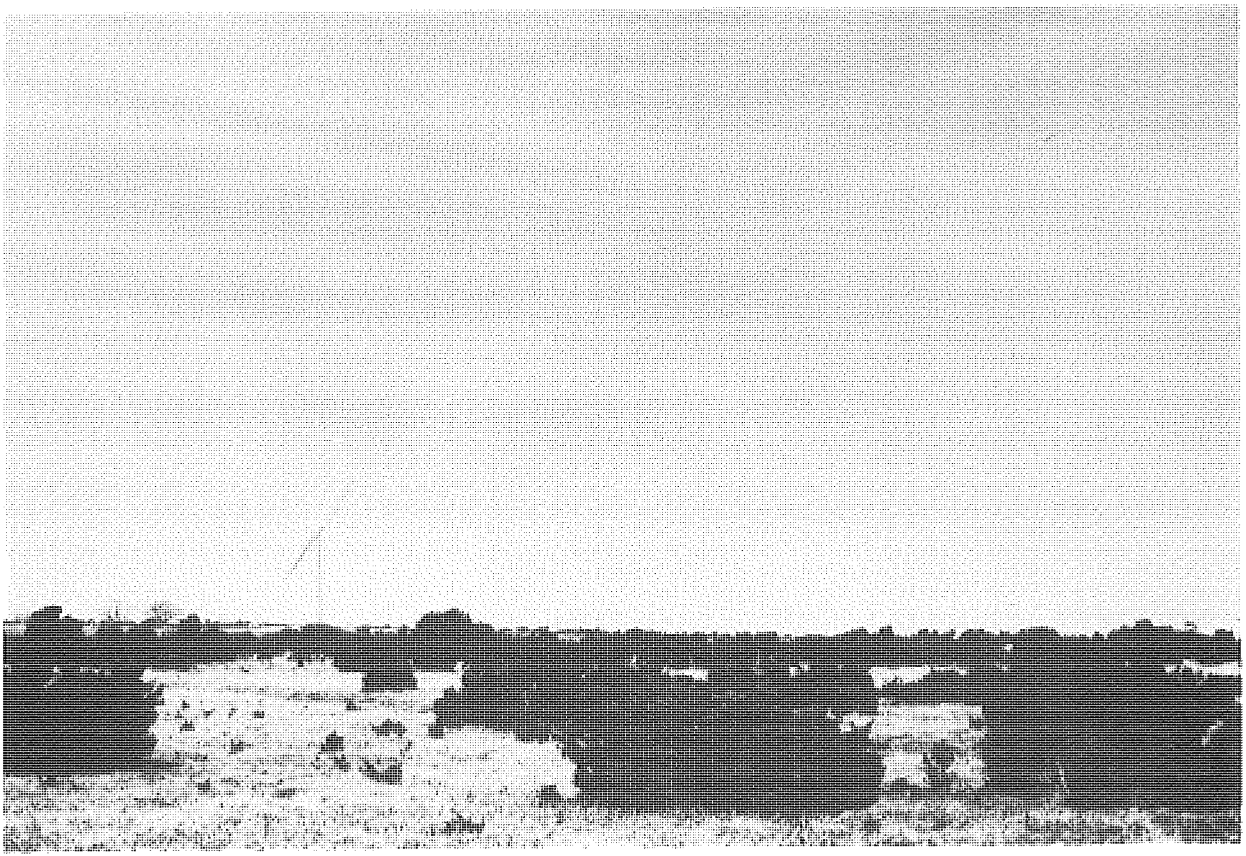


Fig 7. A photo montage of the KaMeWa prototype at the Näsudden site. Distance 2 km.

Anders Høst

THE INFLUENCE OF ENVIRONMENTAL ASPECTS ON THE SITING OF LS WECS.

The National Agency for Physical Planning of Denmark is about to complete a study on the siting of 1.000 - 2.000 windmills. The purpose of the study is to highlight possible problems connected with the siting of such great number of mills.

The Danish wind resources.

A good knowledge of the Danish wind resources is the important basis of this work. It is important for two reasons:

- firstly, it is necessary to know the availability of square kilometres with a good wind energy,
- secondly, it is decisive to know the type of landscape in which the mills are to be sited, in order to describe the conflicts.

The survey of the Danish wind resources is made by considering certain physical structures of the landscape and not, like in most other countries, through a large number of wind measurements. The Danish procedure is based on the fact that all over the country in a height of 500 - 1.000 metres above earth, Denmark has, statisticly seen, the same amount of wind energy. On the surface, the differencies in the wind energy is caused by the variating landscape which is more or less braking the wind. We are talking about the roughness of the landscape. In Denmark, the number of houses and trees are decisive for the roughness of the landscape.

On the basis of maps containing exactly this kind of information, Denmark is devided into 4 groups of landscapes of which the roughness and thereby the wind energy is defined.

From the definitions it turns out that a certain type of landscape has the most attractive areas for siting windmills. Therefore, it is natural to concentrate on the environmental problems connected with the siting of windmills in these areas.

The windmill influence on environment.

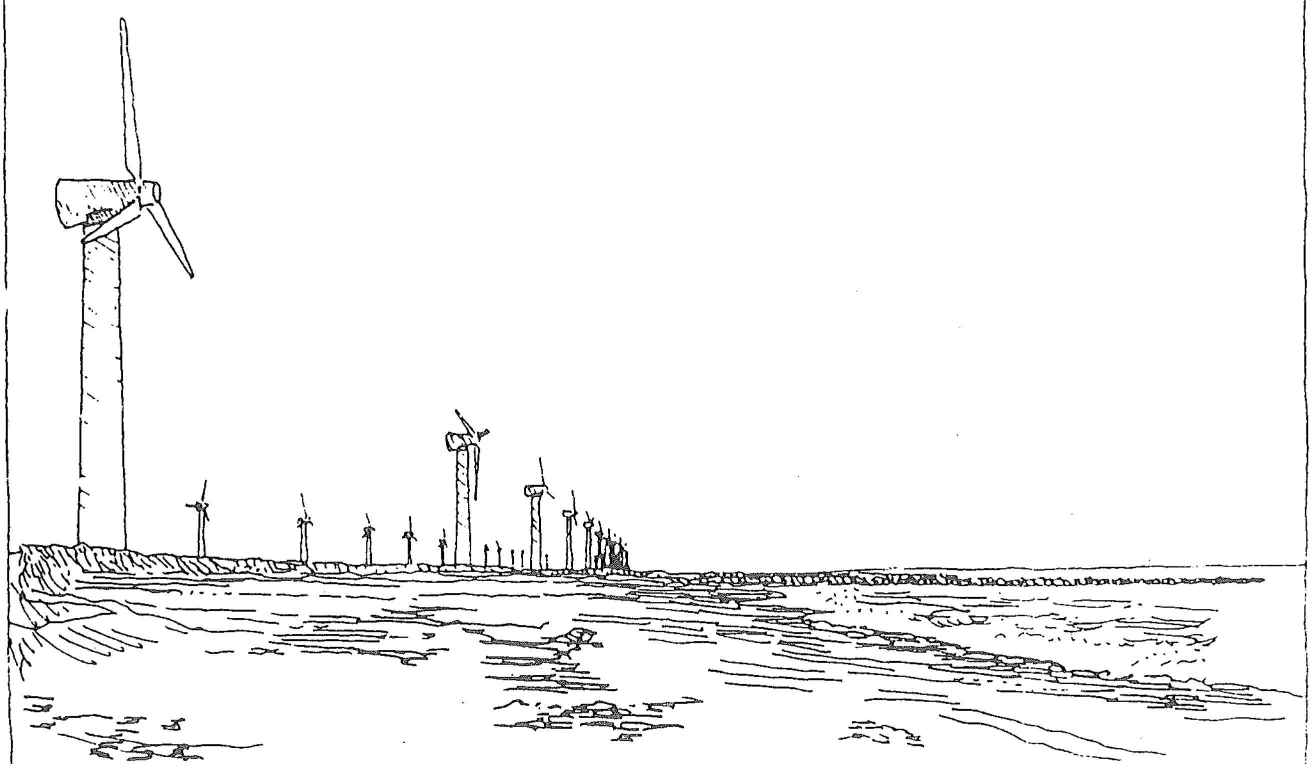
A windmill in function is influencing the environment in several ways. The most important aspects are the following:

A. Visual affect on the landscape
B. Birds' collision
C. Accidents caused by windmill average
D. Noise
E. Interference with telecommunications

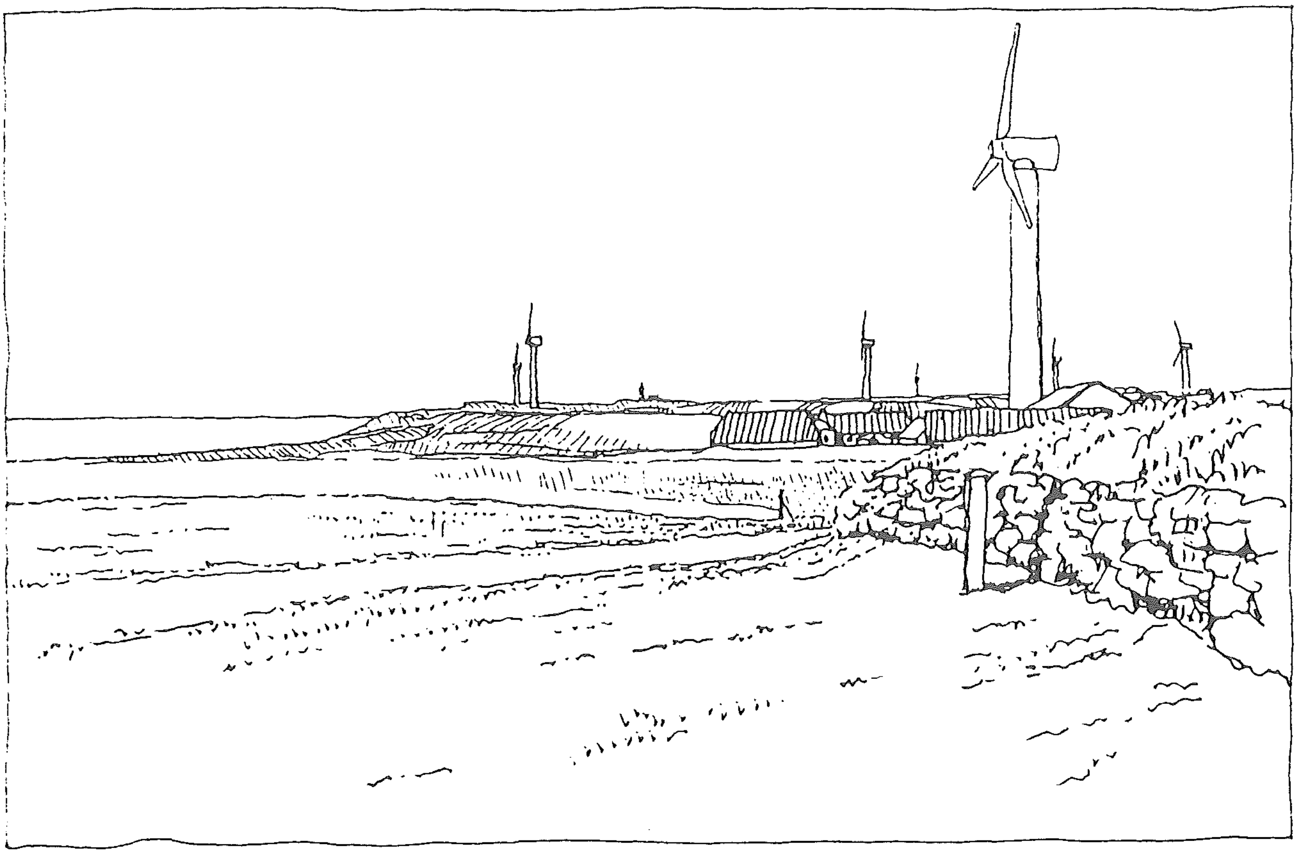
A. Visual affect on the landscape.

When siting windmills in most attractive areas (with most wind energy), the mills are visible on a very long distance owing to the open landscape. Our investigations state that the windmills near Nibe in clear weather are seen up to a distance of 5 - 6 kilometeres, and a cluster of mills will, therefore, have a massive affect on the landscape.

These aspects have been studied by taking photos of different landscapes and from these photos drawings have been made with some windmills in the landscape.



This illustration show a great number of windmills sited in two rows in a very open and flat area.



This illustration show windmills sited in small groups in an agricultural area. The windmills are not sited in any kind of pattern and are not subordinated dominating elements in the landscape.

The first siting of windmills seems the most acceptable solution because the windmills emphasize the endless landscape.

The siting in the second area gives great problems because the structure of the landscape dissapears completely. At the same time, the great dimensions of the windmills are emphasized by houses and trees.

On account of this study, the windmills must be sited in completely open areas. Unfortunately, these areas are so few that not all of the 2.000 windmills can be sited there, and as you will soon see, other conflicting interests are connected to these areas.

B. Birds' collision.

There exists quite a lot of knowledge about birds' collision with lighthouses, radio towers and highvoltage lines. It is known that the birds hit these elements which they have not observed during their flight. To escape collision, the different elements must be visible to the birds.

It is also known that the birds' migration routes lay in the areas with the highest wind energy. Further, that their flying hight in strong wind coincides with the hight of windmills.

How much this knowledge shall influate on windmills - their construction and siting - is an open question as no studies have been made about birds' collision with windmills.

However, until these studies are made, the Danish bird experts will look upon windmills the same way they look upon radio towers etc. And they will not allow windmills sited in areas where habitats of birds exist.

C. The risk of a windmill average.

The wing of a windmill may break during the running of the mill.

Mr. Maribo Petersen has made some calculations concerning the risk of damages on buildings and human beings. There will be given an account of these calculations later on the meeting.

Here, I shall only mention that, as per the said calculations, part of a wing may be thrown up to 700 metres away from the mill. This means that within this distance damages may occur to buildings and human beings.

In Denmark, only few areas around windmills can be kept clear of buildings up to the said distance. Therefore, damages may occur.

There is no Danish legistation about these problems which are new and can find their solution only through a political interference. We have, therefore tackled the problem from another view to which I shall revert.

D. Acoustic noise.

We all know that running windmills send out noise, a noise which is audible up to hundreds of metres away. Measurings show that the noise is at its maximum in the sheltered side of the mill. Moreover, that it is particularly a question of noise coming from the wings.

As the Danish legislation stipulates 40 dB(A) as the maximum of noise near habitation, the noise from the windmills may represent quite a problem.

The noise limit mentioned above must be taken into consideration when siting windmills. Measurings made on a quite old windmill show that probably a distance of some hundred metres from habitation must be observed. Other measurings are planned to make clear whether this noise limit is observed.

E. Radio disturbances - atmospherics.

Interference with telecommunications originating from windmills influate on all sorts of radio communication. Most important is the influence on the television. It is said that all other problems can be coped with, but if the reception of the television is deteriorated, people shall renounce on windmills.

However, measurings up to now only show small interference from mills with wings made of fibre glass - interference which can be eliminated through small and less expensive improvements of the aerial television receiving set.

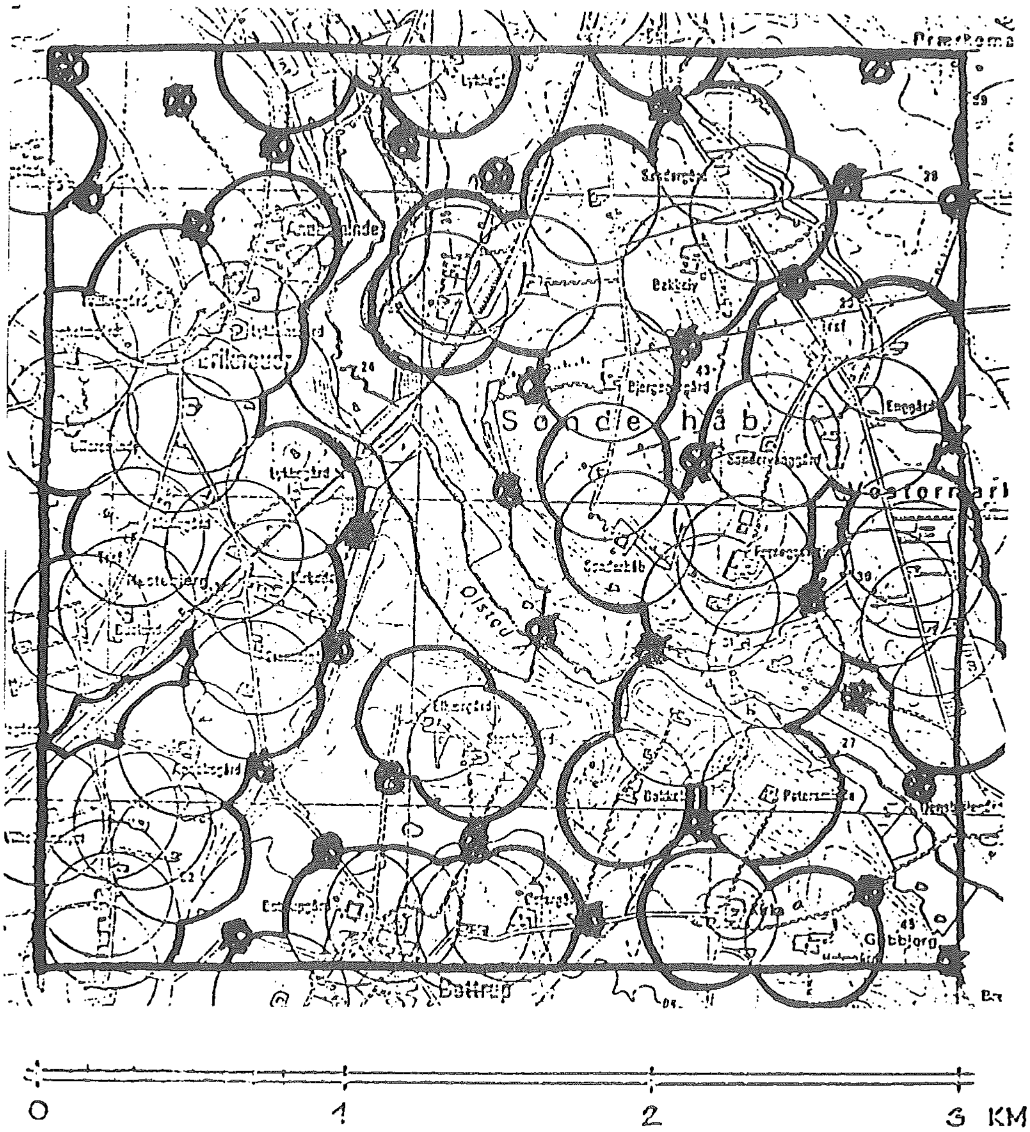
This is the reason why we are not considering these problems a vital argument against the siting of windmills.

Existing and planned landuse in windmill areas.

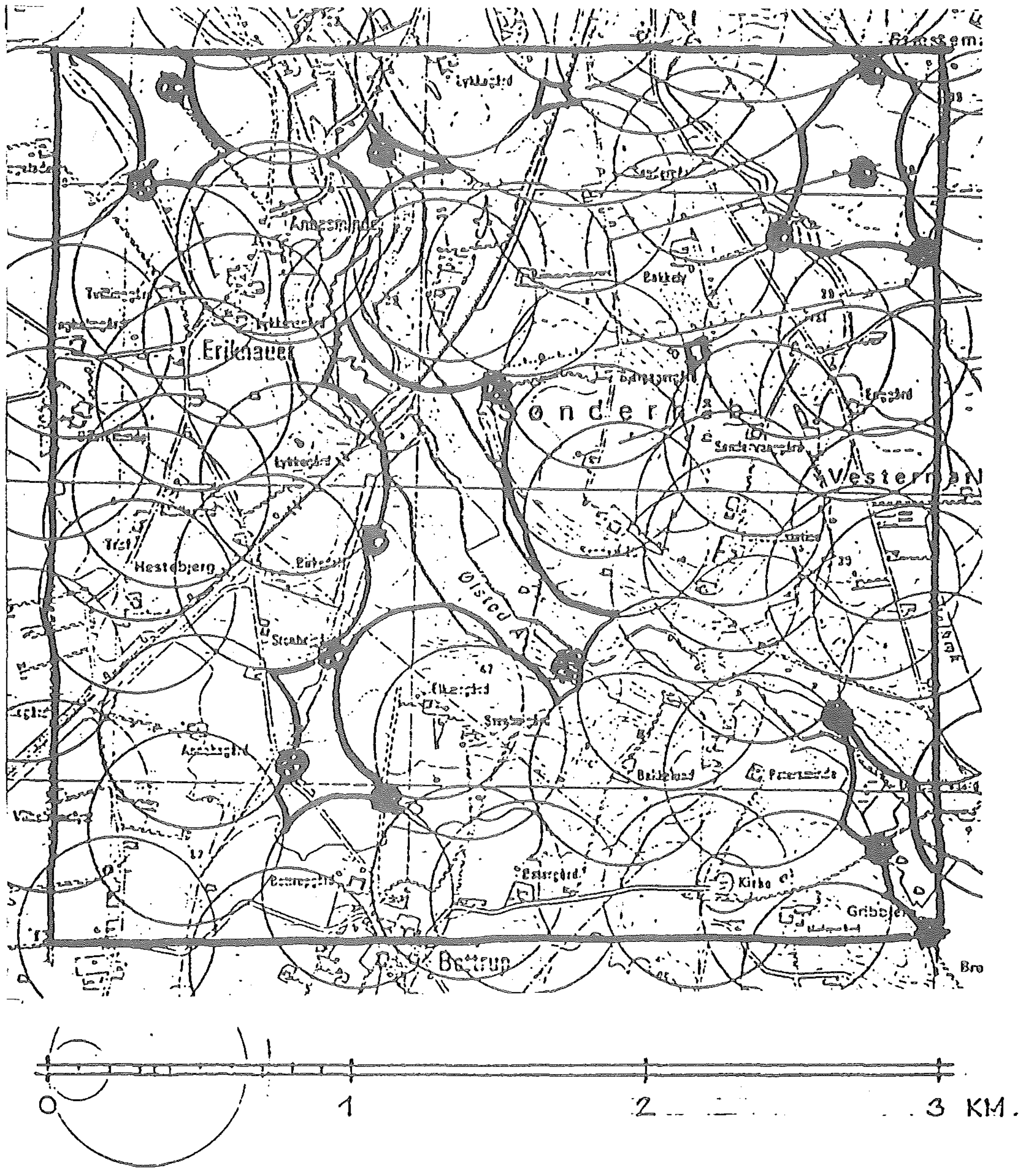
The environmental effects from windmills will create conflicts in many parts of Denmark. To obtain a survey on the importance of the effects, it is necessary to look into the existing and planned landuse or interests connected to certain areas. The most important areas are:

- built-up areas
- habitats of birds
- areas with preserving interests.

As mentioned before, no precise knowledge exists as to the minimum distance of windmills from built-up areas. We have, therefore, chosen to show what is the maximum distance when siting 2.000 windmills in Denmark. Maps have been worked out for the different types of agricultural areas:



- windmills sited in a minimum distance of 200 m from farms and other habitation



- windmills sited in a distance of minimum 300 m from farms and other habitation.

All these maps show that in case of a distance of more than 300 m the siting of windmills is seriously limited.

If the expected legislation about safety on windmills and if new studies on noise from windmills show that a distance of 300 m is too small, it will be necessary to build better windmills with a minimum of noise and a maximum of wing safety.

Denmark has many habitats of birds and most of these habitats are located in the areas with the best wind energy. It will therefore have a decisive influence on the possibilities of windmill siting, if all the bird habitats cannot be used for this purpose.

Denmark is a small country and rather densely populated. Therefore, it has been necessary to make lans and laws to secure that the whole country does not become suburbs and industriel areas. These plans and laws define most agricultural and other open areas as areas to be preserved.

This slide shows a map made by the National Agency for the Protection of Nature. The three different colours indicate the importance of the Agency's interest in preservation.

OVERSIGTSKORT OVER FREDNINGSINTERESSEOMRÅDERS FORDELING

ZONE I Landområder af største interesse

ZONE II Landområder af stor interesse

ZONE III Det åbne land iøvrigt

Statens naturfrednings- og landskabskonsulent 1975

It is clear that these interests will limit the possibilities of windmill siting severely. To give you an impression of how much the reduction in windmill areas are, I will show 3 siting models in a small part of Denmark.

COUNTY OF STORSTRØM

OVERVIEW OF WECS POSSIBLE TO SITE IN AREAS OF ENERGYCLASS A AND B

	SITUATION 1		SITUATION 2		SITUATION 3	
ENERGY-CLASS	A	B	A	B	A	B
AREA						
km²	34	590	30	580	11	302
% of total area	1	17.4	0.9	17.1	0.3	8.4
NUMBER OF WECS I	113	1967	100	1933	37	1007
II	52	908	46	892	17	465
ENERGYPRODUCTION						
GWh/year I	296	4506	262	4429	97	2307
GWh/year II	136	2080	121	2044	45	1065

I : MINIMUMDISTANCE TO BUILDINGS : 200 m
II -"- -"- -"- : 300 m

Situation 1: No consideration of other interests.

Situation 2: No siting of windmills in birds habitats, recreation areas, military areas etc.

Situation 3: All interest into consideration.

The Survey of Suitable Regions for the Erection of Large Scale Wind Energy Converters in the Federal Republic of Germany

L. Henke

1. Summary

Many areas in the Federal Republic of Germany, especially in the coastal regions of the North Sea, are meteorologically suitable for the location of wind energy converters. It is known that various influences restrict these areas, but no concrete data about the real usable wind potential are at present available.

Therefore the Kernforschungsanlage Jülich on behalf of the Bundesministerium für Forschung und Technologie (BMFT) has invited Lahmeyer International GmbH, Frankfurt/Main, to make a study about the real suitability of regions for the erection of large scale wind energy converters.

This paper briefly describes the scope of the study to be performed.

For the evaluation of the usable wind potential, the influences which restrict the suitable areas for converters will be investigated. The remaining areas which are still suitable for large scale wind energy converters are to be determined. These areas will be thoroughly scrutinized. The erection of wind power plants in the range of MW as well as the erection of interconnected networks will be studied.

The main purpose of the study which is presented is to ascertain the real potential of wind energy for large scale wind energy converters which can be used.

The study will start in 1981 and its duration will be of approximately two years.

2. Introduction

Many areas in the Federal Republic of Germany, especially in the coastal regions of the North Sea, are suitable for the location of large scale wind energy converters from the meteorological point of view. Therefore it can be expected that the wind energy conversion can give a noticeable contribution to the energy supply. Unfortunately, various influences restrict these areas. The scope of these restrictions is not yet known, so that at present quantitative statements about the significance of wind energy conversion in the Federal Republic of Germany are not possible.

Therefore the Kernforschungsanlage Jülich on behalf of the Bundesministerium für Forschung und Technologie (BMFT) has invited Lahmeyer International GmbH, Frankfurt/Main, to make a study about:

The Survey of Suitable Regions for the Erection of Large Scale Wind Energy Converters in the Federal Republic of Germany.

The study shall start at the beginning of 1981 and its duration shall be of approximately two years.

This paper briefly describes the scope of the study to be performed.

Only large scale wind energy converters in the range of MW can be considered for such a study, since small converters do not contribute significantly to covering energy requirements and in addition do not raise similar problems concerning their erection.

The GROWIAN1, for example, which has a rated power output of 3 MW, will be used as a standard size for the study (1).

The investigations to be carried out in the study will be extended to the off-shore areas of the German North Sea. This is meaningful from the meteorological point of view and also possible because of only minor environmental restrictions. Anyhow in this study, the special technical problems of off-shore plants concerning the erection for example will only slightly be touched upon in respect to duration and scope of the study.

On the basis of areas limited by meteorological reasons the restrictions by various influences will be evaluated and the remaining areas which are suitable for large scale wind energy converters will be listed.

The aim of this study will be to obtain a clear statement concerning the wind energy potential which can be used by large scale converters in the Federal Republic of Germany.

3. Content of the Study

3.1 Areas with Adequate Wind Characteristics

A basis for the study shall be the report of the German Weather Service with the title "Wind Conditions in the Federal Republic of Germany in View of the Wind Power Utilisation" (2). Only areas with wind velocities above approximately 5 m/s at 10 m above ground as per attached figure 1 will be interesting for examination in the study. Therefore a meteorological data collection and compilation will be performed.

These data will be scrutinized in view to the use of wind power. The result will form the wind data basis which will contain information such as

- measuring stations, descriptions
- orographic data, general meteorological data
- atmospheric diffusion and thermal lamination
- geostrophic wind conditions
- recordings and averages of wind velocities
- duration of adequate wind conditions
- temporal influences.

A grid will be placed over the areas with allotments of attributes such as

- orographic data, roughness length
- attributes of boundary layer
- area coordinates, heights
- meteorological data
- measuring stations.

The present wind data collection probably will have to be improved to get the relevant information about

- average wind velocities, variation of wind velocities
- frequency distribution
- wind direction distribution
- horizontal extrapolation
- vertical extrapolation, etc.

Then this basis will be subject to analysis in order to check the completeness and the suitability for the further stages of the study.

One result may be that the evaluation of additional measurement data from ground stations in the respective areas or data of measurements of tower stations will be recommended. Another result may be that short-time measurements for the synthetizing of existing long-time measurements or special measurements on TV or cooling towers, e.g. for additional information about wind distribution, change of the wind direction, vertical components, etc. will be recommended.

The next stage will be the calculation of the gross wind energy potential in the lower boundary layer as well as the ascertainment of temporal influences.

In areas with complex terrain, for example in the highlands, only upper limits of available wind energy will be calculated, because the theoretical basis for the determination of the average wind profile and the spectrum of turbulence do not yield results adequate for wind energy evaluation.

3.2 Determination of the Areas Suitable for Large Scale Wind Energy Converters

The evaluation of suitable areas will start in the off-shore areas of the German North Sea with the highest wind velocities from 10 to 200 m above ground and be then extended to the coastal regions with lower wind velocities. The study will also refer to some small territories in the German highlands which will prove suitable for the purpose. These areas in Germany suitable from the meteorological point of view are limited by various influences. The evaluation of these influences will be performed by the method of elimination of non-suitable sites. Therefore a catalogue of criteria will at first be compiled.

In addition present day planning policy on governmental and regional decision levels with influences ranging into the future will be considered.

The criteria for sites which obviously are not suitable are:

- residential districts, sport facilities and others
- industrial and trade areas.

In addition the following areas for example are not suitable for the use of wind power:

- streets, roads including parking places
- water ways including ports
- railways with stations

- routes of electric lines, transformer substations
- bird migration routes
- radio links, microwave highways
- pipelines
- airports, low level flight areas
- sailing lines, courses of ships.

Furthermore the areas of protected and prohibited regions are to be excluded such as:

- nature reserves
- parks
- woodlands
- military areas, e.g. troop training areas.

When all the criteria are selected and defined they will be subject to an evaluation. For that purpose the special requirements of wind power plants regarding their site will be considered. With the aid of these criteria it will be possible to reach a weighted evaluation of each single site and at least to eliminate the fundamentally not suitable areas.

The next step will be the investigation of the suitable areas because of the following criteria which enable a more detailed evaluation, as for example:

- topographical features regarding the wind conditions
- minimum space required for the station
- location regarding the electric network
- infrastructure such as roads, water supply, sewage, telephone connnections
- adequate foundation conditions.

The results will be inscribed in suitable maps and the determined areas will be characterized with their important qualities in a clear catalogue, to enable a classification of the stations and/ or areas for stations.

Several areas which were desk evaluated will then be inspected in order to clarify if their real qualities are in accordance with the evaluated ones. It will depend on the results of the study if a location for one plant or whole regions will be inspected. When results are known, a decision can be reached if photos made by satellite or inspection from the air of the respective large areas are necessary for evaluating wind power plant sites.

3.3 Detailed Evaluation of the Gross Wind Energy Potential in Selected Suitable Areas

The present meteorological data will be critically and thoroughly checked concerning their use as a basis for quantitative data about the gross wind energy potential in selected suitable areas.

The wind data basis will be completed to obtain more information about boundary layer, scattering of wind velocities, turbulence coefficient, distribution of wind velocities in micro-areas, etc. The aim of this stage of the study will be to ascertain the gross wind energy potential and the gross performance data in the boundary layer up to approximately 200 m above ground in selected characteristic areas.

3.4 Catalogue of Wind Energy Converters to be Considered

In order to determine the limits of the potential which is really usable for wind energy converters it will be necessary to analyse the design and technical characteristics of wind energy converters which will be available at the time of the study. Furthermore, development trends should also be considered for the determination of power plants in the MW range, so that statements for the usable potential of wind power can be made, which will be still valid when the erection of the wind power plant might be realised.

For this analysis the following criteria will mainly be scrutinized:

- size of the units
- design and overall dimensions
- construction model
- plant layout
- power characteristics
- control characteristics
- area required
- geological requirements
- environmental disturbances
- operation safety
- availability of the plant
- periods of maintenance
- present regulations and regulations to be expected (environmental reasons for example) concerning wind energy converters.

3.5 Determination of Wind Energy Converters in the Range of MW Suitable for the Evaluated Areas

There are various criteria for establishing plant types and sizes adequate for different areas. Depending on the plant, the topographical conditions and, for example, the infrastructure as well as the layout of the network, different plant designs will be necessary.

The location of converters in the suitable areas will be ascertained. Furthermore the connections to the network will be proposed. In respect to the specific converter data the usable wind potential will be ascertained under consideration of the results of the preceding parts of the study.

Three typical areas as examples will be scrutinized. For these, off-shore, coastal, and highland areas, typical specific plant data including the real usable wind potential will be determined. The results will be transferred to plants with similar conditions in the same region.

3.6 Interconnected Networks for Wind Power Plants

On the basis of preliminary investigations the areas which are large enough for the compound location of wind energy converters are not very numerous in the Federal Republic of Germany. If the areas are large, the total usable wind potential will be approximately the sum of the usable wind potential of the single units. If a concentric arrangement is chosen and the available space is restricted, the total useful potential will be considerably diminished. Therefore an optimisation of the arrangement of wind energy converters might be necessary.

Data of the networks will be collected in the respective areas in cooperation with the utilities operating in the area. Networks which are in the construction or planning stages will also be considered.

The relevant data of the power generation by converters will be compiled. This compilation contains the number of wind power stations, their geographical location in the investigated area, the rated power, the voltage level, etc.

The characteristic wind power generation of interconnected stations will be ascertained such as

- yearly power generation
- variation of the yearly power generation
- seasonal performance duration curves
- yearly performance duration curves.

The reduction of the usable wind potential and the influence on the performance characteristics will be estimated depending on (besides converter design):

- arrangement density of the wind converters
- energy dissipation
- typical arrangement of converters
- wind direction.

A summarising demonstration of the potential usable for the wind converters will be performed. In addition configurations of the interconnected grids will be proposed.

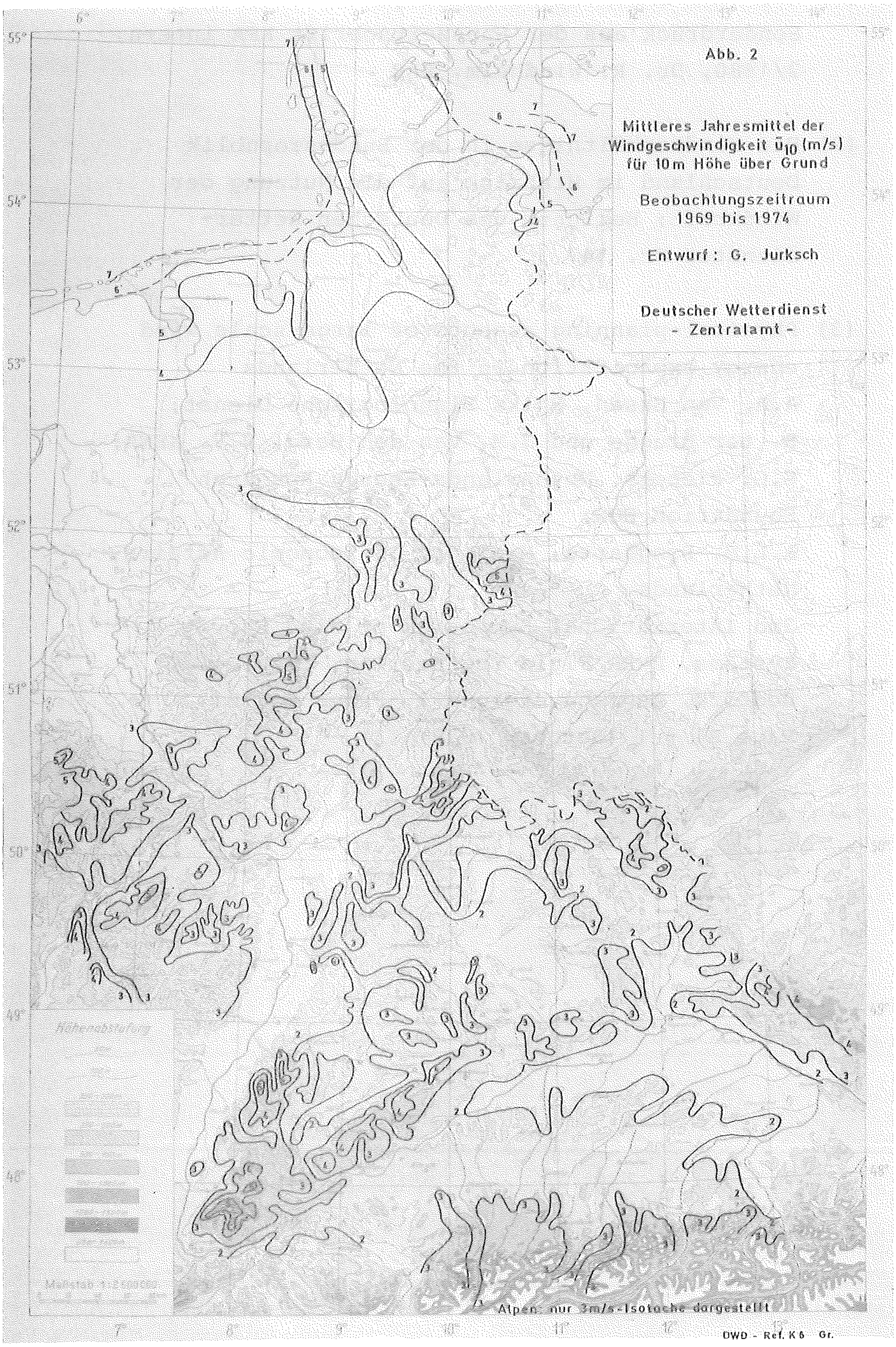
3.7 Comparison of the Usable Wind Potential for Large Scale Converters with the Wind Potential Based Only on Meteorological Data

The purpose of this part of the study will be to demonstrate the difference between the gross wind energy potential based on meteorological data and the usable real potential. Additionally, the results might be useful for critically scrutinizing meteorological data in view of the utilisation of wind power (3). On the other hand, the results of the comparison may be a basis for transferring the conclusions reached to regions in other countries with similar conditions.

3.8 Results

The results of the study will be compiled in a final report. The further procedure in the matter of wind energy utilisation will be discussed. Results which deviate from the present experience will be especially mentioned. Their impact will be analysed and evaluated.

Figure 1: Mean average of the year of the wind velocity $\bar{u}_{10}$ (m/s) for 10 m above ground level quoted from reference 1



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ENVIRONMENTAL CONSIDERATIONS FOR LARGE WIND TURBINE SYSTEMS:

BLADE ICING PROTECTION

A
PRESENTATION
BY

JOSEPH M. SAVINO

BLADE ICING PROTECTION

BACKGROUND

- FLYING ICE IS A SERIOUS HAZARD TO PEOPLE AND EQUIPMENT
- ICE ON BLADES MIGHT UNBALANCE THE ROTOR CAUSING VIBRATION AND EXCESSIVE STRESSES
- ROTOR PERFORMANCE COULD BE DEGRADED
- SMITH-PUTNAM MACHINE BLADES SHED ICE

BLADE ICING PROTECTION

MOD-OA WTS ICING EXPERIENCE AT CLAYTON, NEW MEXICO

- ICE FIRST SHED FROM BLADES IN MARCH 1978
- LARGE PIECES OF ICE (1 CM THICK x 10 TO 20 CM LONG) FOUND ON GROUND UP TO 60M FROM MACHINE
- ICING OCCURS DURING FOG WHEN TEMPERATURES ARE NEAR FREEZING AND DURING FREEZING RAIN
- ICE HAS FORMED ON ROTATING BLADES WITHOUT FORMING ON TOWER
- POWER HAS DROPPED FROM RATED (200 KW) TO ZERO IN STEADY WIND
- NO INCREASE IN ROTOR BLADE LOADS HAS BEEN OBSERVED

BLADE ICING PROTECTION

BASIC ASSUMPTIONS

- ICE FORMS FIRST ON MOVING BLADES
- ICING RATE ON STATIONERY BLADES IS MUCH LOWER THAN ON MOVING BLADES
- ICING CONDITIONS ARE USUALLY SHORT-TERM AND TRANSIENT
- SHUTDOWN DURING ICING PERIODS WILL RESULT IN MINIMAL LOST OPERATING TIME

BLADE ICING PROTECTION

CHARACTERISTICS OF ICING DETECTION SYSTEM

- FUNCTION: TO SENSE BLADE ICING AND SHUTDOWN WTS

- SENSING PROBE (AIRCRAFT TYPE)
  - AN AXIALLY VIBRATING PROBE
  - NATURAL FREQUENCY WITHOUT ICE = 40,000 HZ
  - NATURAL FREQUENCY WITH 0.020 INCH ICE LAYER = 20 HZ

- PROBE POWER REQUIREMENTS: 28 V. DC FOR OPERATION; 115 V FOR PROBE HEATERS

- PROBE LOCATION ON MOD-OA BLADES
  - LOW PRESSURE SIDE
  - MID-SPAN & MID-CHORD
  - 45 MPS RELATIVE WIND SPEED ENVIRONMENT
  - 17G RADIAL ACCELERATION FIELD

- COST: $2000 PLUS INSTALLATION

BLADE ICING PROTECTION

EXPERIENCE WITH ICE DETECTION SYSTEM

- VERIFICATION TESTS WERE RUN IN NASA ICING RESEARCH TUNNEL (CLEVELAND, OHIO) UNDER SIMULATED OPERATING AND FEATHERED CONDITIONS
- INSTALLED ON MOD-OA WTS IN CLAYTON, NEW MEXICO; IN NOVEMBER 1978
- INITIATES SHUTDOWN DURING ICING CONDITIONS
- DETECTOR SYSTEM IS RELIABLE AND PROVIDES ADEQUATE PROTECTION
- 30 HOURS DOWNTIME PER YEAR RESULTED FROM IDS OPERATION AT CLAYTON
- IDS NOW SPECIFIED FOR MOD-1, MOD-2, AND FUTURE MACHINES

ON SAFETY DISTANCES FROM WINDMILLS

by

B.Maribo Pedersen & J.A.Chr.Bugge

Summary:

This report marks the beginning of the work concerning safety distances from windmills.

The event treated is an object being hurled away from an operating rotor. The two kinds of objects considered are

a) lumps of ice shed from the wing tips at normal operation during icing conditions and

b) wreckage torn off the rotor in connection with a breakdown of the windmill.

The probability of a given impact area being struck by a hurled object is calculated as a function of the distance from the windmill in dependence of tip speed and assumed drag coefficients.

Paper presented at the 5th expert meeting under the IEA-agreement for co-operation in the Development of LS/WECS,

"Environmental and Safety Aspects of the present LS/WECS".

Munich 25/26 September 1980

1. INTRODUCTION

The risk of damage, especially on persons, caused by an operating rotor plays an important role in the search for adequate sites for large windmills.

Due to limited amount of experience the treatment of this question contains a considerable uncertainty. This applies both to the risks during normal operation (e.g. ice shed off) and to the occurence and progress of breakdowns.
A detailed analysis of the mean time between failures for a typical windmill construction has been beyond the scope of this work. In the examples given, a value of 0.01 $year^{-1}$ has been used; this is the value assumed for the Nibe windmills. Likewise there has not been suggested any specific level for the acceptable risk of damage on persons; this is ultimately a political question.

The attempt of this work has been to calculate the probability by which a hurled object will impact within a given area as a function of the distance from the windmill, the tip speed of the rotor and the assumed drag coefficients.

All calculations are based on a rotor diameter of 50 m, and a hub height of 50 m.

2. SPECIFICATION OF THE PROBLEM

In this work the term safety distance is defined as the least distance from a windmill to domestic and residential areas which guarantees a certain maximum frequency of damage to a residing person.

In estimating the value R of the safety distance it is required to establish the values of the following terms:

1) The accepted frequency H_{acc} of a residing person being affected by a hurled object.

2) The probability $s(r)$ that a hurled object affects a person residing in a fixed distance r from the windmill.

3) The frequency h of an object being hurled from the rotor.

H_{acc} is due to a choice whereas it is possible to estimate the values of $s(r)$ and h.

The value of R is determined by the following conditions:

$$h \times s(r) = H_{acc} \quad \text{for} \quad r = R$$

$$h \times s(r) < H_{acc} \quad \text{for} \quad r > R \quad .$$

3. TREATMENT OF THE PROBLEM

The probability $s(r)$ is estimated for each of the objects:

- a whole wing
- the outer third of a wing
- a flake of ice
- a cube of ice

As it is seen, only objects hurled off the rotor is treated; the downfall of stationary parts is not considered, as it is beforehand assumed, that the safety distance in any case at least equals the total height of the windmill.

3.1 Assumed dimensions and speeds

3.1.1 The rotor

Hub height: 50 m
Rotor radius: 25 m
Total height: 75 m

To investigate the influence of the rotational speed the following wing-tip speeds has been applied:

1) 70 m/s
2) 100 m/s
3) 140 m/s
4) 200 m/s

It is observed, that each succesive speed marks a doubling of the centrifugal force on the wings.

3.1.2 The hurled objects

Two consequences of a breakdown are considered, namely the hurling of one whole wing and the outer third of one wing respectively.

Besides that, the shedding of ice from the wing tips during icing conditions is treated.

Two shapes are considered, namely flakes and cubes. During the formation the ice layer more or less has the shape of a flake. However in shedding, these flakes might break into minor pieces, some of which have denser shapes.

Dimensions:

	1/1 wing	1/3 wing	flake of ice	cube of ice
Length, m	25	8	0.25	0.05
Mass, kg	3000	350	1	0.125
Area, m^2	46	8	0.05	0.0025
Radius, m	8	21	25	25
Mass to area ratio kg/m^2	65	44	20	50

Table 3.1.1

The area corresponds to the largest cross-section, while the radius corresponds to the centre of gravity, c.g.

3.1.3 Amount of icing

Corresponding to the observations at two Danish meteorological stations during a decade, the mean annual amount of icing on a stationary surface is estimated to 5 mm/year.

This is converted to a mean annual amount of icing on the wings during operation of around 1200 kg/year. distributed as:

600 ice flakes of 1 kg
600 ice flakes of 0.875 kg
600 ice cubes of 0.125 kg

In the calculations all the ice flakes are treated equally, i.e. the considered distribution corresponds to:

1200 ice flakes of 1 kg
600 ice cubes of 0.125 kg.

3.1.4 Division of the region of impact

In the computations, the area around the windmill is divided into concentric circular rings, each having a width of 10 m . For each circular ring ($r_2 = r_1 + 10$ m) the probability $S(r_1,r_2)$ of impact by an actually hurled object is computed. The sum of all values $S(r_1,r_2)$ is 1 .

3.1.5 Impact area

As basis an adult person in an arbitrary position is chosen. This yields a sphere with a radius of 1 m .
This sphere is supposed situated at a distance r from the windmill.

It is now assumed that the person is affected by a hurled object, if the centre of gravity passes so closeby, that the furthest end may touch the sphere. I.e., if the distance from the trajectory of the c.g. to the centre of the sphere is less than (1+L) m , L being the distance from the c.g. to the furthest end.
The corresponding area is:

$$A = \pi \cdot (1+L)^2$$

Values of A:

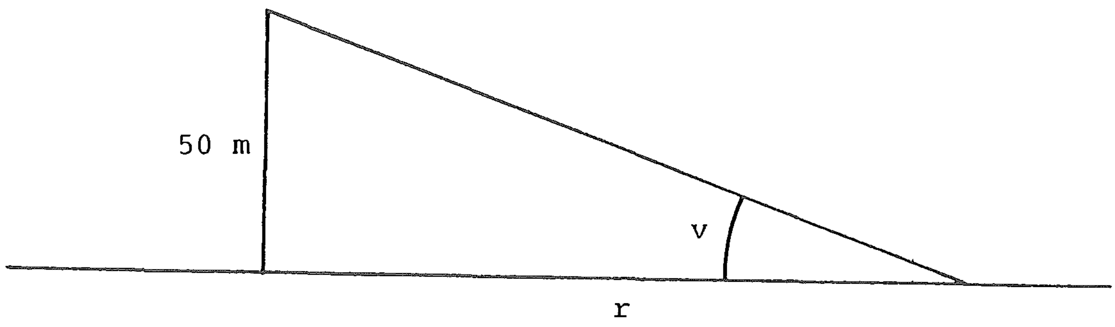
Object	1/1 wing	1/3 wing	flake of ice	cube of ice
L, m	17	4	0.16	0.04
A, m^2	1018	79	4	3

Table 3.1.2

The corresponding area on a horizontal surface is:

$$A_v = \frac{A}{\sin v} ,$$

where v designates the impact angle. In the following v is set equal to the angle under which the hub is seen, i.e.:



$$v = \mathrm{Arctan}(50/r)$$

This yields the value:

$$A_v = \frac{\pi \cdot (1+L)^2}{\sin(\mathrm{Arctan}(50/r))}$$

Values of the ratio A_v/A at different distances r :

r m	0	50	100	150	200	250
A_v/A	1	1.4	2.2	3.2	4.1	5.1

Table 3.1.3

It is observed, that the impact area grows considerably with the distance.
The probability of a residing person being affected by impact at a distance r from the rotor is found by dividing the quantity $A_v \cdot S(r_1, r_2)$ by the area of the regarded circular ring. r being chosen as $(r_1+r_2)/2$, this area is approximately $20 \cdot \pi \cdot r$, and the probability is found as:

$$s'(r) = \frac{A_V \cdot S(r_1, r_2)}{20 \cdot \pi \cdot r} = \frac{(1+L)^2 \cdot S(r_1, r_2)}{20 \cdot r \cdot \sin(\mathrm{Arctan}(50/r))} .$$

As far as the whole wing or the outer third of a wing is concerned, the object is assumed to slide, roll or skip a further distance ℓ away from the windmill.
The ultimate probability is thus:

$$s(r) = \frac{(2\ell+1+L) \cdot (1+L) \cdot S(r_1, r_2)}{20 \cdot r \cdot \sin(\mathrm{Arctan}(50/r))} ,$$

which is related to the distance $r+\ell$ from the windmill.

The value of ℓ is set to:

$$\ell = \begin{cases} r/3 & \text{for} \quad r < 75 \text{ m} \\ 25 \text{ m} & \text{for} \quad r \geq 75 \text{ m} \end{cases}$$

If a subject of a different extension (e.g. a building) is considered, it is necessary to adjust the computed values.

3.2 Computational method

The trajectory of the c.g. is computed ballistically from initialvelocity, gravity and drag using the computer programme described in [1].

The equations of motion used in the programme has the form:

$$\ddot{x} = - K \dot{x} \sqrt{\dot{x}^2 + \dot{y}^2 + (\dot{z} - v_w)^2} - g$$

$$\ddot{y} = - K \dot{y} \sqrt{\dot{x}^2 + \dot{y}^2 + (\dot{z} - v_w)^2}$$

$$\ddot{z} = - K(\dot{z} - v_w) \sqrt{\dot{x}^2 + \dot{y}^2 + (\dot{z} - v_w)^2}$$

where

$K = \frac{1}{2} \cdot \rho_{air} \cdot C_D \cdot \frac{\text{Area}}{\text{Mass}}$ and v_w is the wind speed, x is height above ground level, y is distance from the windmill in the direction of throw and z is the distance in direction of the wind.

At a given wind speed and position of the wing in question the distance between the windmill and the impact + further displace-

ment is computed.
This is performed for all combinations of operational wind speeds and wind positions round the clock yielding the probability distribution which expresses the probability, that a randomly hurled object will end up within a given circular ring. Multiplication with the probability that a residing person is affected here yields the sought probability of damage to persons.

3.3 Assumptions

Here it is tried to account for the assumptions and simplifications used.

3.3.1 Number of hurled objects

In the case of icing it is assumed, that all the freezing rain, met by the wings will adhere and freeze.

In the case of breakdown, only one object is assumed to be torn off and hurled. The possibility of e.g. all wings breaking off is thus disregarded.

3.3.2 Position of wing

The probability of throw-off is considered to be equal for all angular positions of the rotor.

Thus the influence from the

- gravitational force
- wind gradient
- gyro forces

is neglected.

3.3.3. Trajectory

As a solitary wing or a part thereof has no position of equilibrium in flight, the possibility of gliding is disregarded. Likewise the irregularities due to transitory lift in various directions are neglected.
The trajectory is computed from simple ballistics including drag.

In case of flakes or cubes of ice the drag coefficient C_D is set equal to 1 in connection with the area A in table 3.1.1; a flake is assumed to undergo a rapid, uniform rotation between broadwise and edgewise position. A cube will experience a C_D of approximately 1 regardless of the position.

Due to the larger size the rotation of a wing or wing tip is slower. The application of a constant drag coefficient without a more thorough investigation therefore seems dubious. For this reason a wide span of values has been applied in the computations.

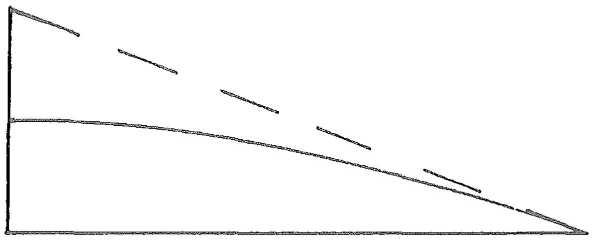
3.3.4. Impact area A

The extent of the impact area A perpendicular to the trajectory is chosen according to the assumption, that the hurling object will undergo violent rotations at the impact and therefore assume any possible position here.
As this is not physically possible, the assumption is considered conservative.

3.3.5 Impact angle v

The trajectory of an object hurled in vacuum is a parabola. The impact tangent is directed towards a point at double the height over the topmost point of the trajectory.
Thus the angle v under which the hub is seen from the impact point corresponds to hurling in vacuum from the wing tip in the lowest position.

Expect for a minor area without interest in the vicinity of the windmill this angle is on the safe side in all cases. The real impact angle is larger than stated here due to drag.



3.3.6 The additional displacement

The chosen value is based upon a rough estinate.

3.3.7 Operational winds speeds

The field of operation is set to 4 - 21 m/s. The distribution of wind speeds is taken from the measurements at 56 m height on the meteorological tower at Research Establisment RISØ.

3.4. Results

3.4.1 Ice

Figs. 3.4.1 and 3.4.2 show the function s(r) for flakes and cubes of ice respectively. As mentioned earlier, the drag coefficient is set to 1 in both cases.

As far as the flakes are concerned no influence of the rotational speed has been detected. Due to the low mass to area ratio (20 kg/m^2) the flakes are almost immediately caught up and carried by the wind.
On the contrary the rotational speed has a distinct influence on the part of the cubes, where the mass to area ratio is 50 kg/m^2.

3.4.2 Wings and wing tips

Figs. 3.4.3 and 3.4.5 show s(r) for a whole wing (mass to area ratio = 65 kg/m^2). Again an obvious dependence of the rotational speed is seen together with an appreciable influence of the assumed drag coefficient.

Figs. 3.4.6 and 3.4.8 show s(r) for the outher third of a wing with a mass to area ratio of 44 kg/m^2. Here the influence of the assumed drag coefficient is very significant. In figs. 3.4.3 and 3.4.8 the further displacement is included.

Figs. 3.4.9 and 3.4.10 show the trajectories at a tip speed of 100 m/s with various assumptions for the drag coefficient for a whole wing and the outer third of a wing respectively. In all cases the longest trajectory is shown.

Figs. 3.4.11 shows the maximum horizontal throw as a function of C_d. Especially for the outer third of a wing the distance increases considerably as the assumed value of C_D is decreased.

From the above it is seen that the assumed value of C_D has a decisive influence on the distance of flight especially for the outer third of a wing.

As no evidence has been found against it, a flight with slow rotation and low drag has been considered possible. Therefore an average drag coefficient as low as 0.1 cannot be disregarded without further investigations.

3.5. Application

The probability s(r) of damage to persons read from figs. 3.4.1. and 3.4.8. refers to an actually hurled object. In order to arrive at an expected frequency of damage to persons H the procedure stated in chapter 2 is applied. I.e. the value of s(r) is multiplied by the frequency of occurence of an object beeing thrown off.

To find the total frequency of occurence of damage to persons the individual values of H for the objects in questions must be added together. With the assumptions that the safety distance exceeds 100 m and the tip speed is 140 m/s the diagrammes can be simplified as suggested by the dotted lines.

At known values of h the diagrammes can be combined in one single graph.

Application of ice detectors which stop the windmill in case of icing is reckoned to reduce the value of h_{ice} by a factor of 100.

Fig. 3.5.1. shows a combined diagram with the following assumptions:

Ica: Without ice detector	h_{flakes}	1200	$year^{-1}$
	h_{cubes}	600	$year^{-1}$
With ice detector	h_{flakes}	12	$year^{-1}$
	h_{cubes}	6	$year^{-1}$

V_{TIP} = 100 m/s, C_D = 1

Wing and wing tip $h = 10^{-2}$ $year^{-1}$

V_{TIP} = 140 m/s, C_D = 0.1-1

The diagram is drawn for $r \geq$ 100 m

It is observed that the dominant risk factor up to 200 m is impact of ice.

Between 200 m and 260 m the risk is determined by hurling of a whole wing.

Above 260 m the only possible cause of damage is hurling of the outer third of a wing.

By use of ice detectors the frequency af damage can be reduced from approximately 10^{-1} to 10^{-3} per year within 200 m from the windmill.

Above 200 m the use of ice detectors plays no role.

With acceptable frequencies of damage H_{acc} of 10^{-4}, 10^{-5} and 10^{-6} per year, the values of safe R are 260, 310 and 710 m respectively.

4. CONCLUDING REMARKS

In judging the results stated in this report it is important to pay attention to the assumptions and the uncertainties stated.
Especially the uncertainty as regards to the drag coefficient is very unsatisfactory as the latter might well prove to be the decisive term in the calculation of safety distance.
It is therefore deemed necessarry to carry out a more precise dynamical analysis of the flight including a thorough computation of the rotations. It would be necessary to supplement the analysis with experiments in an adequate scale.

Other factors of importance are the frequency $h_{breakdown}$ of breakdown and the choice of H_{acc}.

The estimation of $h_{breakdown}$ requires a detailed analysis of the windmill construction in question. However it should be possible to abtain far lower values than the 10^{-2} per year applied in the example.

The choice of H_{acc} is ultimately a political one. In [2] some american investigations on the subject are mentioned. To judge by this a value of 10^{-4} - 10^{-6} per year might be expected. According to the conclusions stated here values between 10^{-4} and 10^{-6} per year might turn out to be acceptable.

5. REFERENCES

[1] Safety of wind energy conversion systems (WECS)
Preliminary study
Appendix B (side 123 - 128)

FFA Report HU-2126

[2] Reactor safety study, WASH-1400,
United States atomic energy commission, Aug.1974.

Fig. 3.4.1.

s(r) for cubes of ice

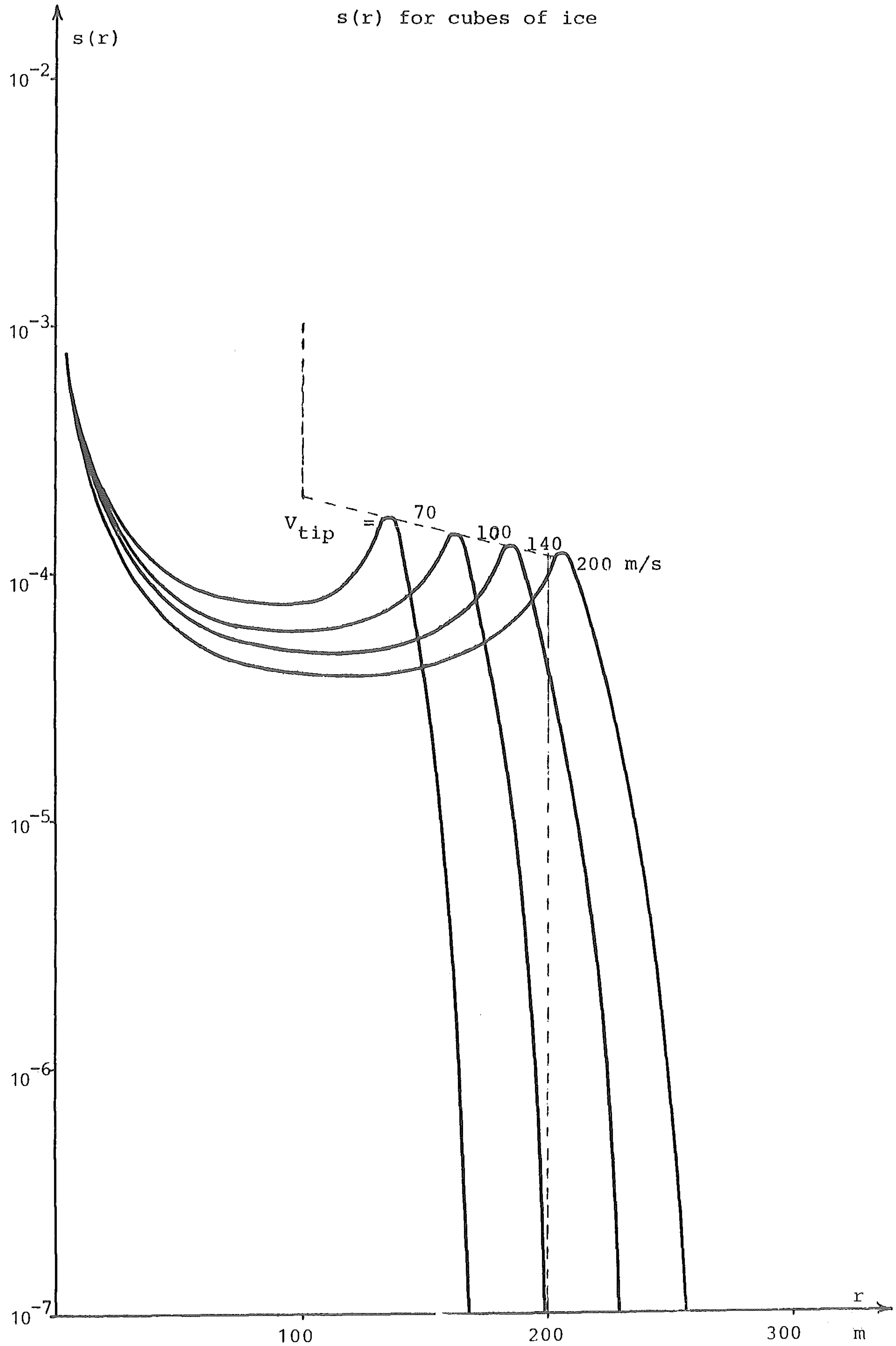


Fig. 3.4.2.

s(r) for ice flakes

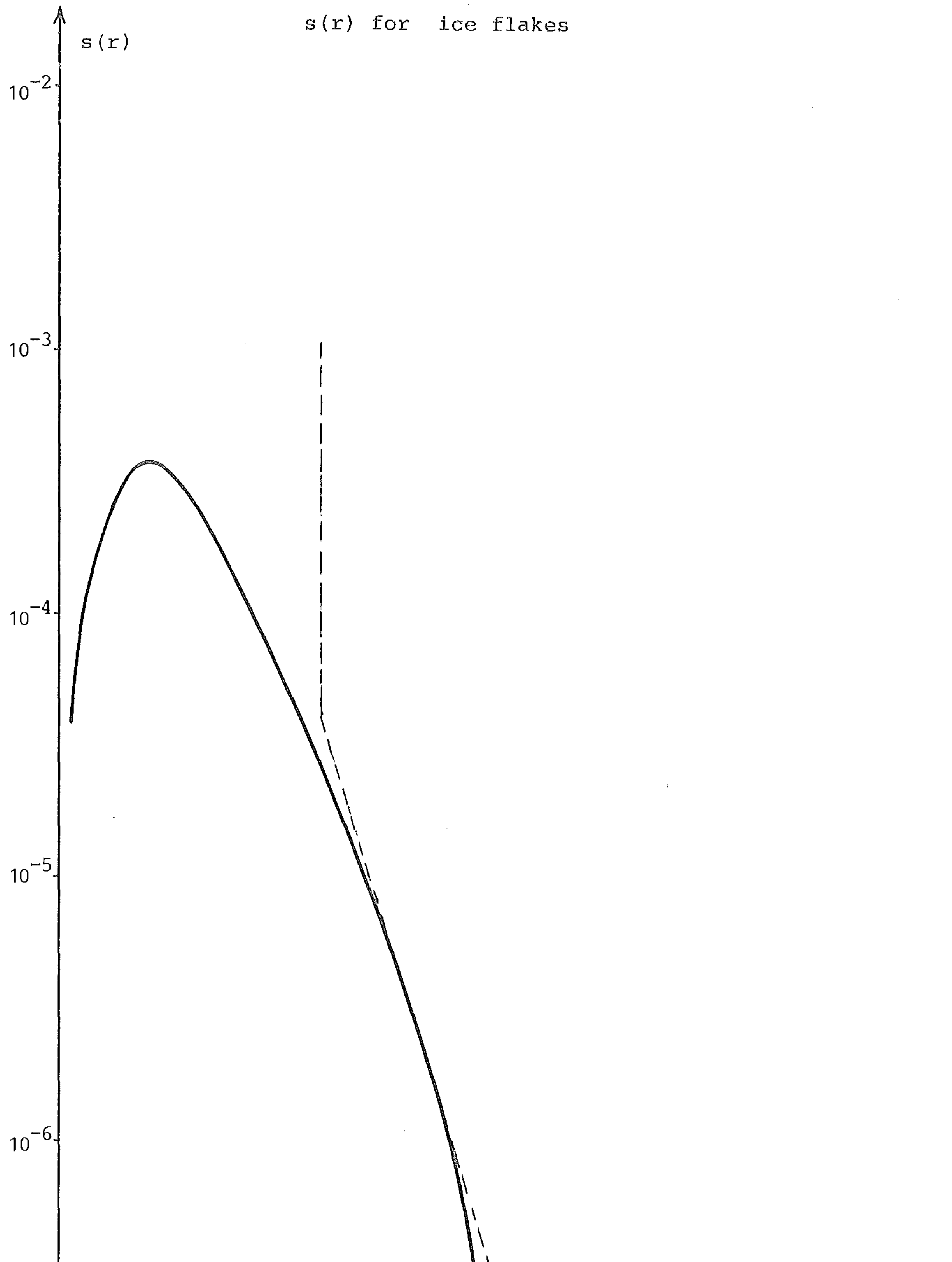


Fig. 3.4.3.

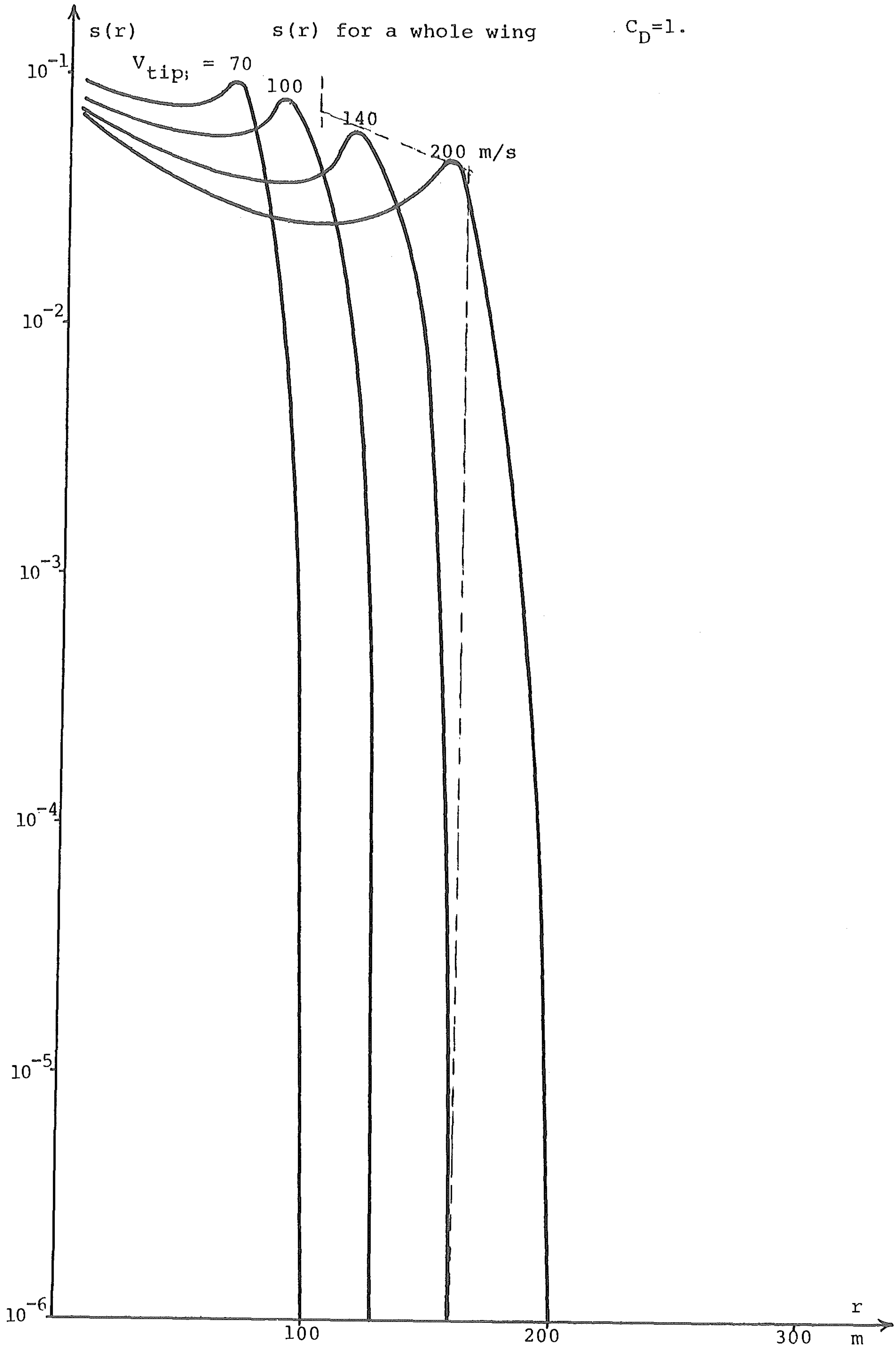

s(r)
s(r) for a whole wing
C_D=1.
V_{tip} = 70
100
140
200 m/s
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
100
200
300
r
m

Fig. 3.4.4.

s(r) for a whole wing , $C_D = 0.5$

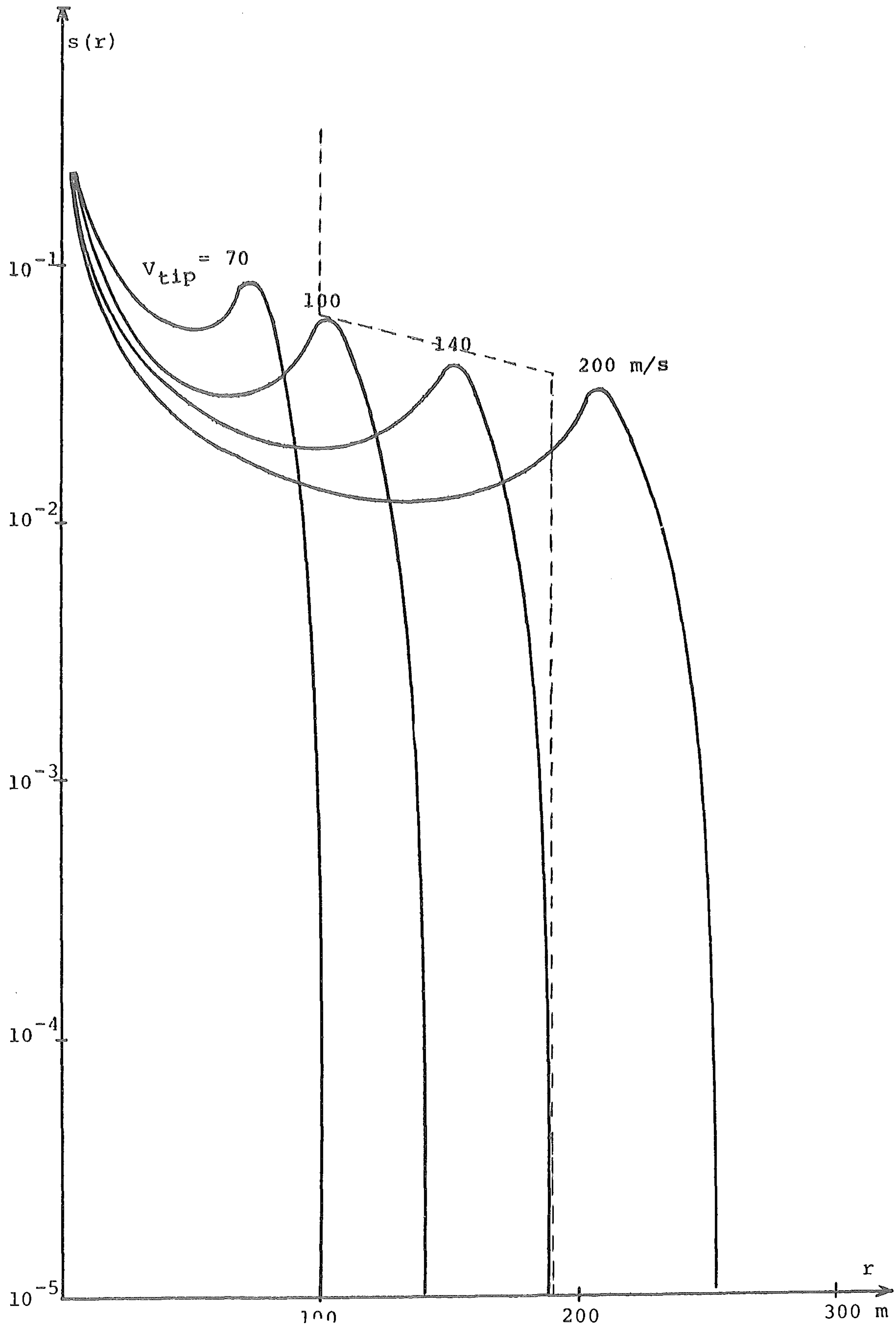


Fig. 3.4.5.

s(r) for a whole wing, $C_D = 0.1$

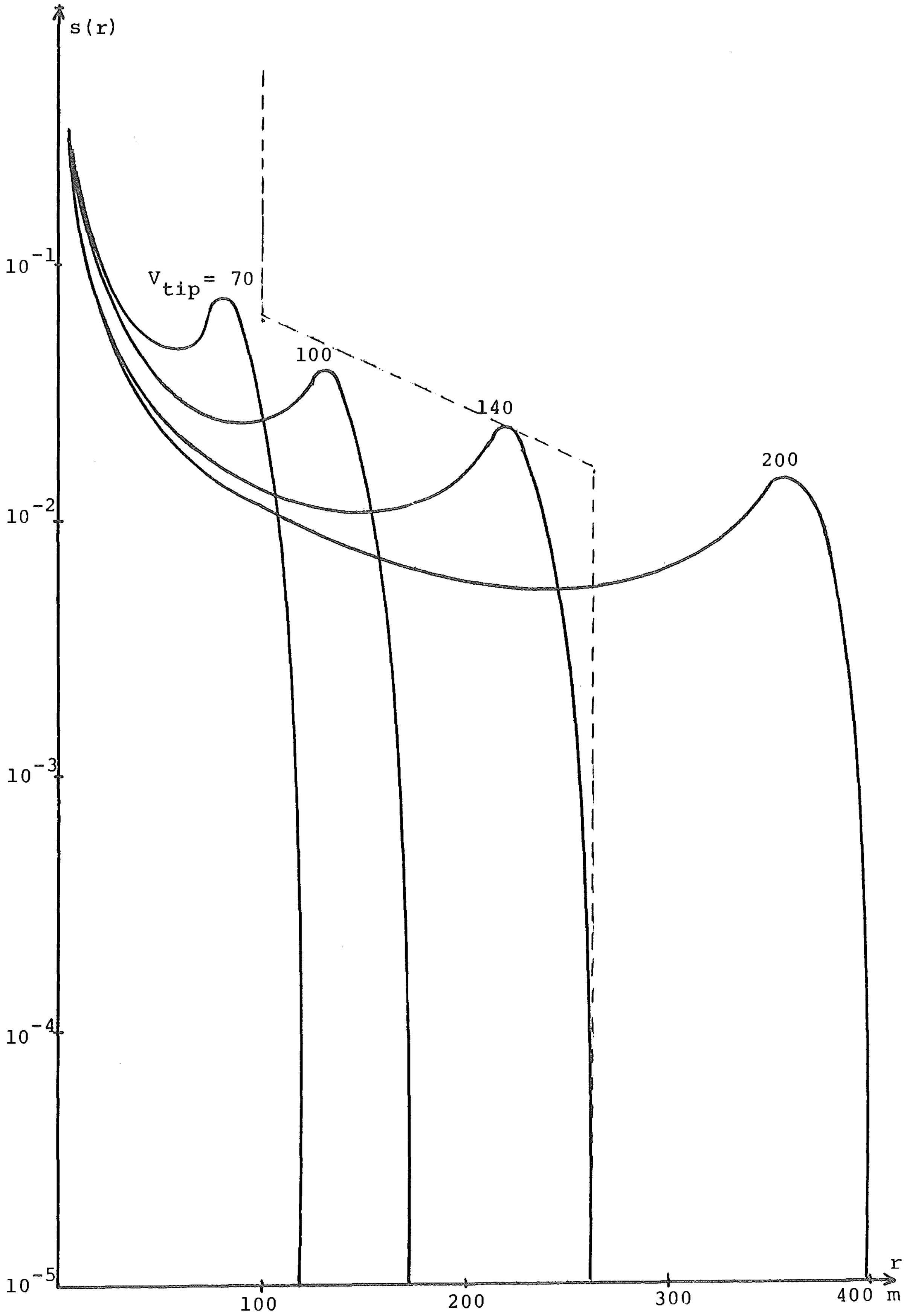


Fig. 3.4.6.

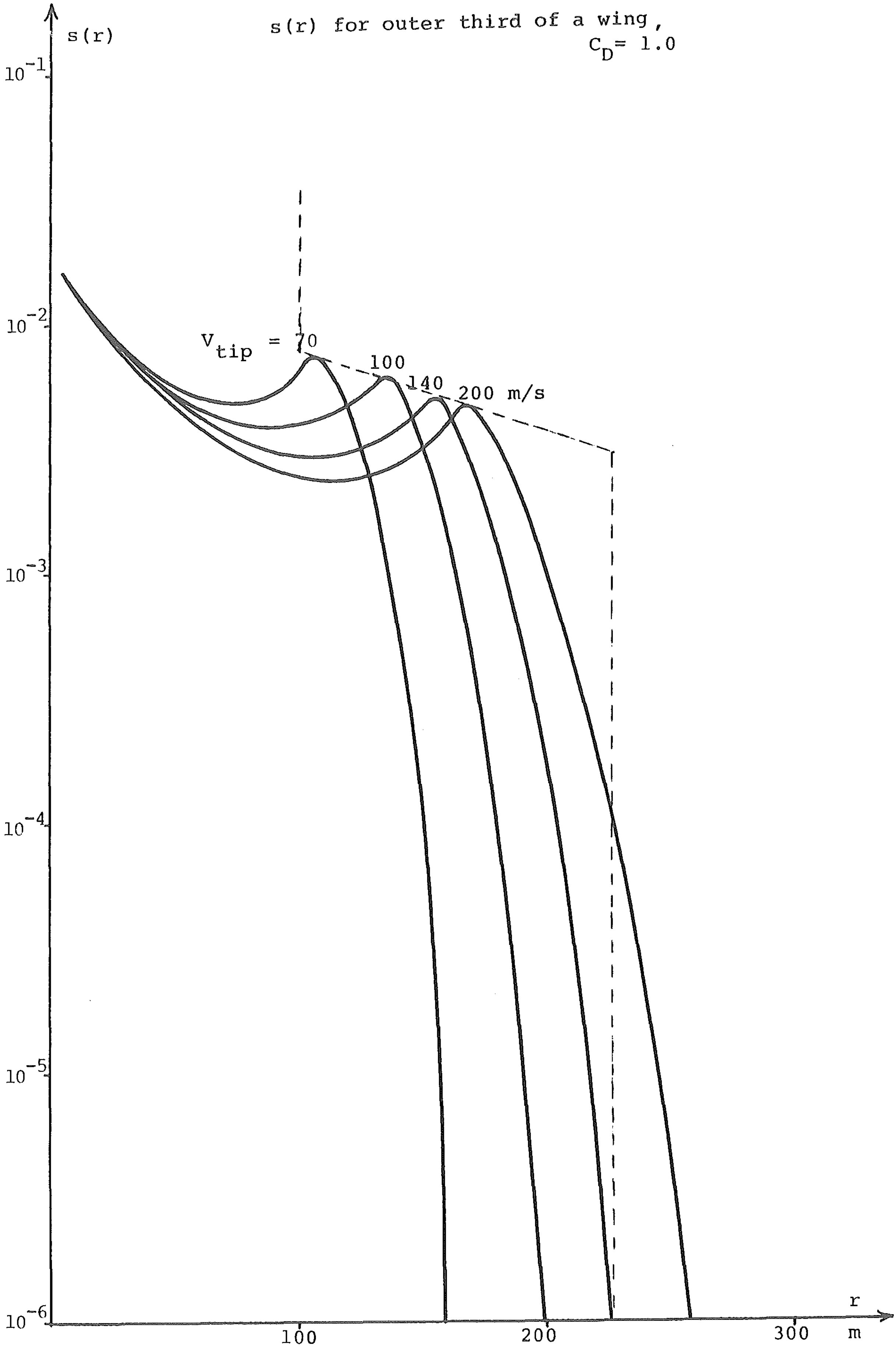

s(r)
s(r) for outer third of a wing,
C_D= 1.0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
V_{tip} = 70
100
140
200 m/s
100
200
300
r
m

Fig. 3.4.7.

s(r) for outer third of a wing, C_D = 0.5

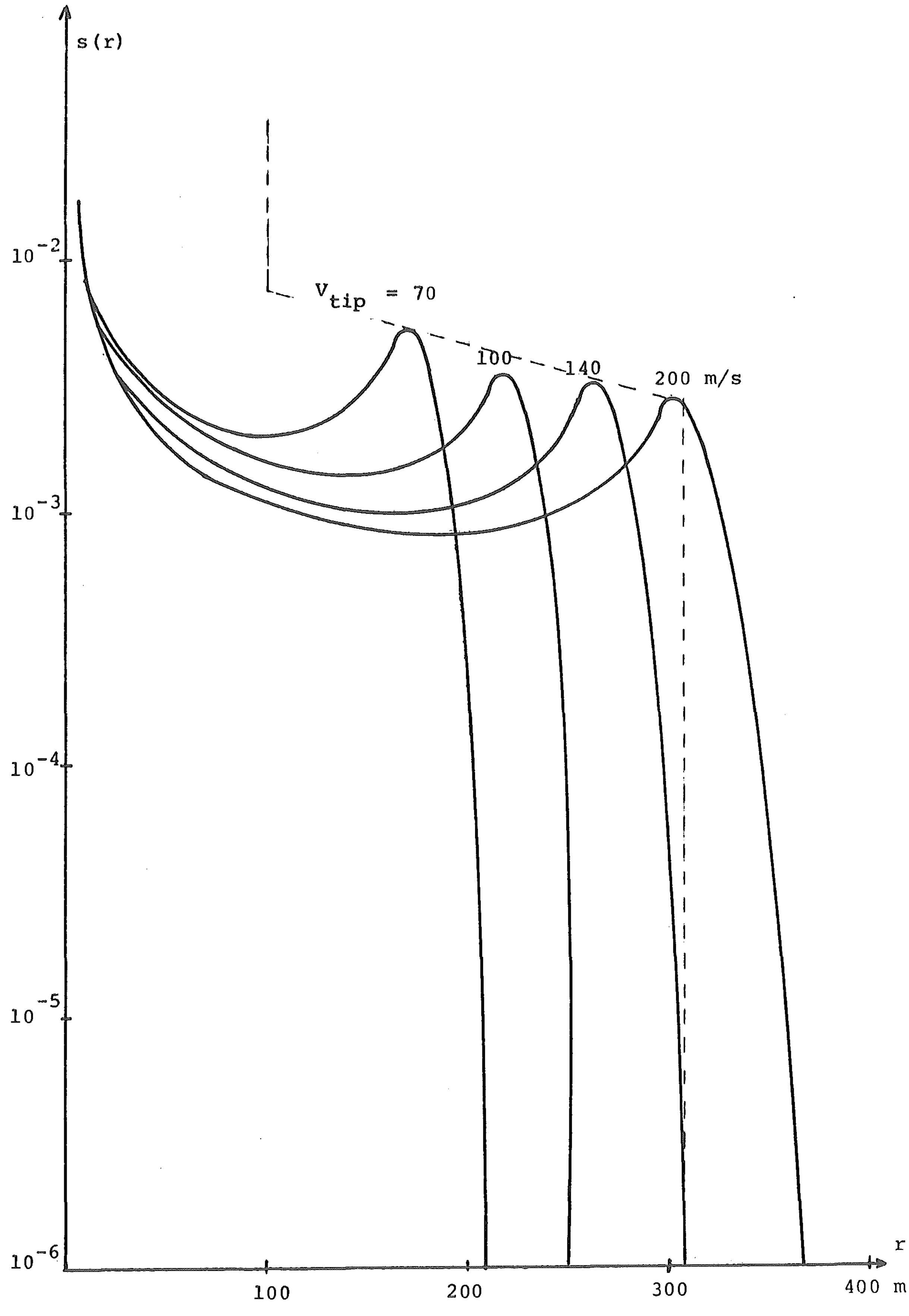


Fig. 3.4.8.

s(r) for outer third of a wing, $C_D = 0.1$

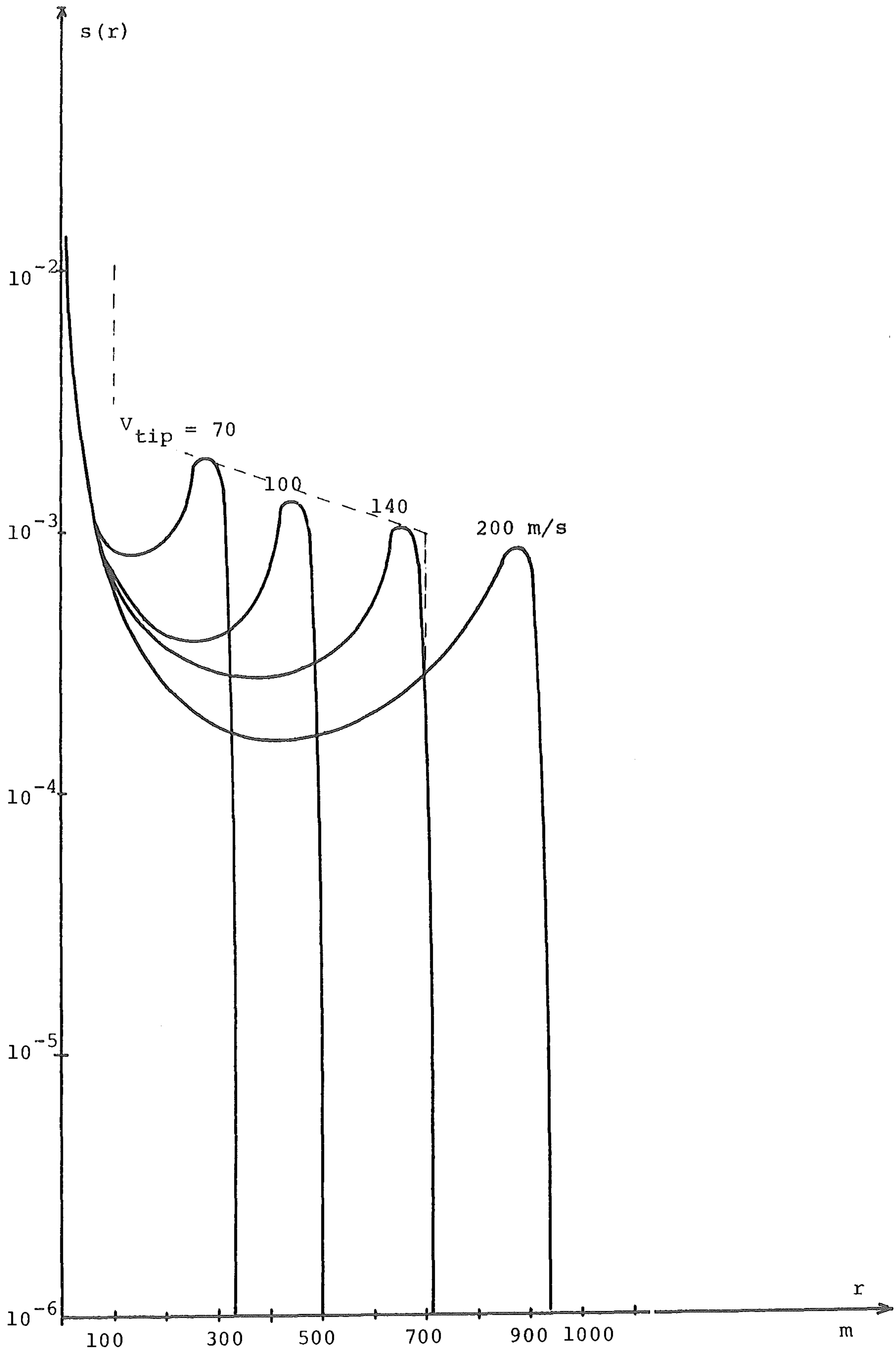


Fig. 3.4.9.

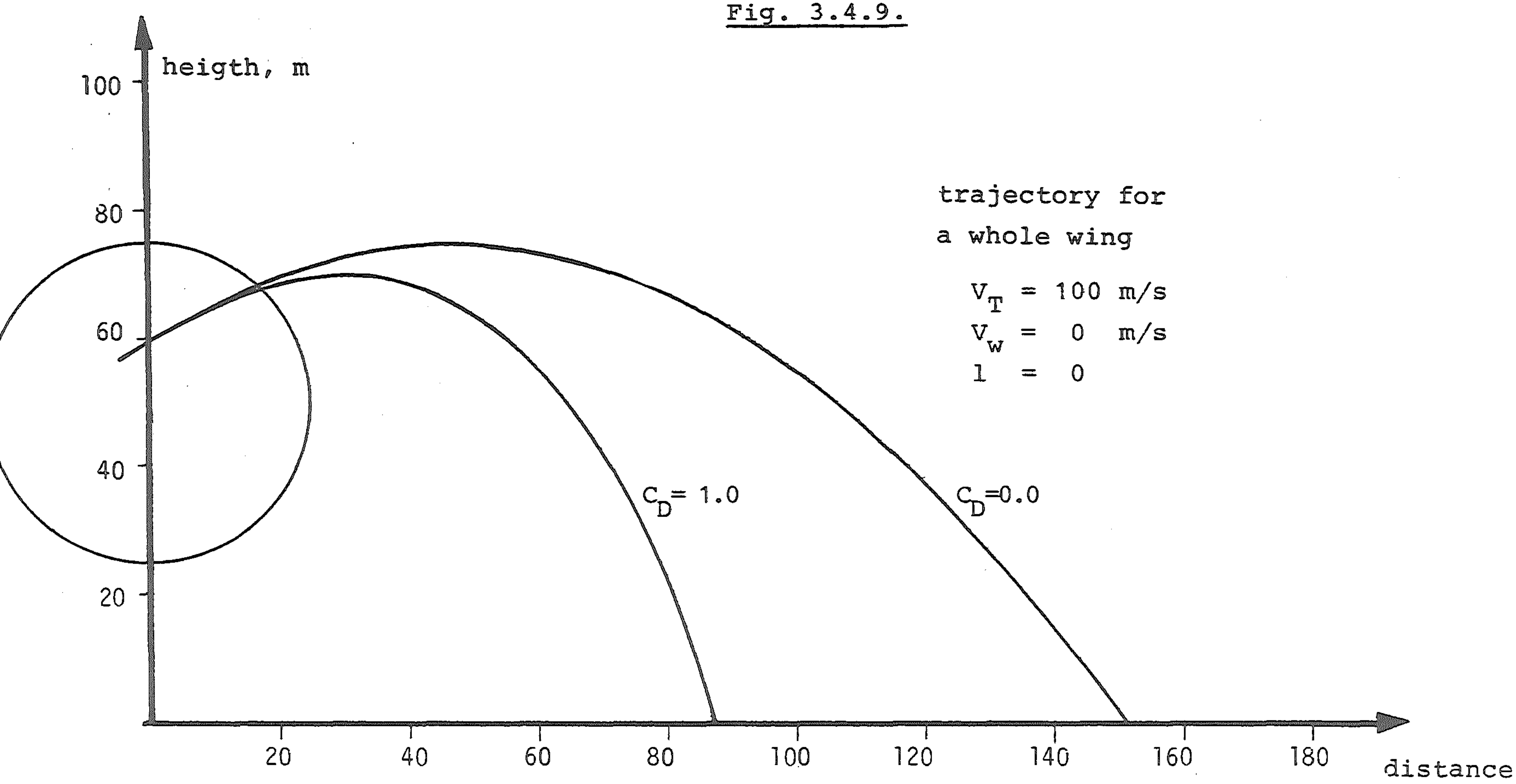

heigth, m
100
80
60
40
20
20
40
60
80
100
120
140
160
180
distance
trajectory for
a whole wing
V_T = 100 m/s
V_w = 0 m/s
l = 0
C_D= 1.0
C_D=0.0

Fig. 3.4.10.

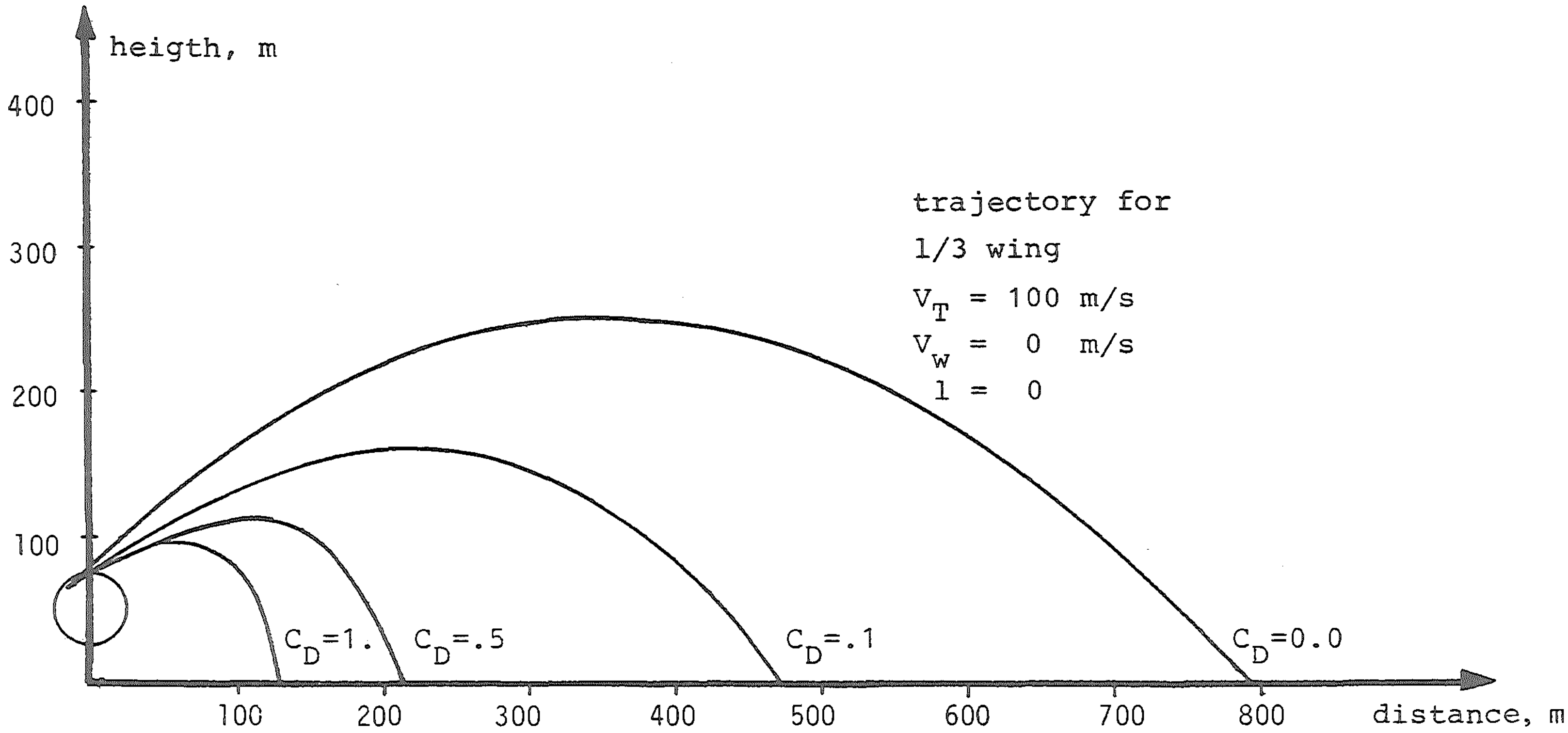
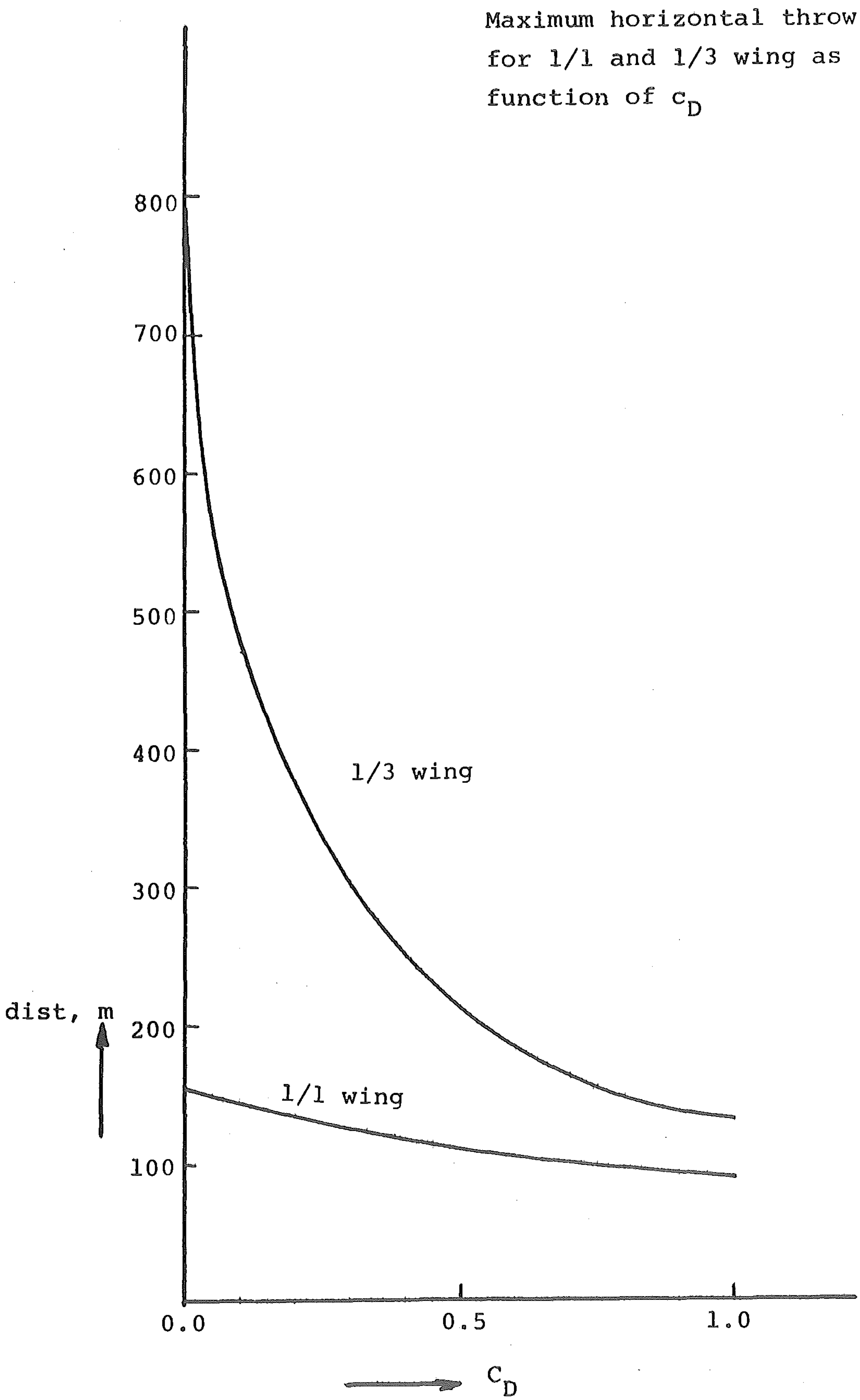

heigth, m
400
300
200
100
trajectory for
1/3 wing
V_T = 100 m/s
V_w = 0 m/s
l = 0
C_D=1.
C_D=.5
C_D=.1
C_D=0.0
100
200
300
400
500
600
700
800
distance, m

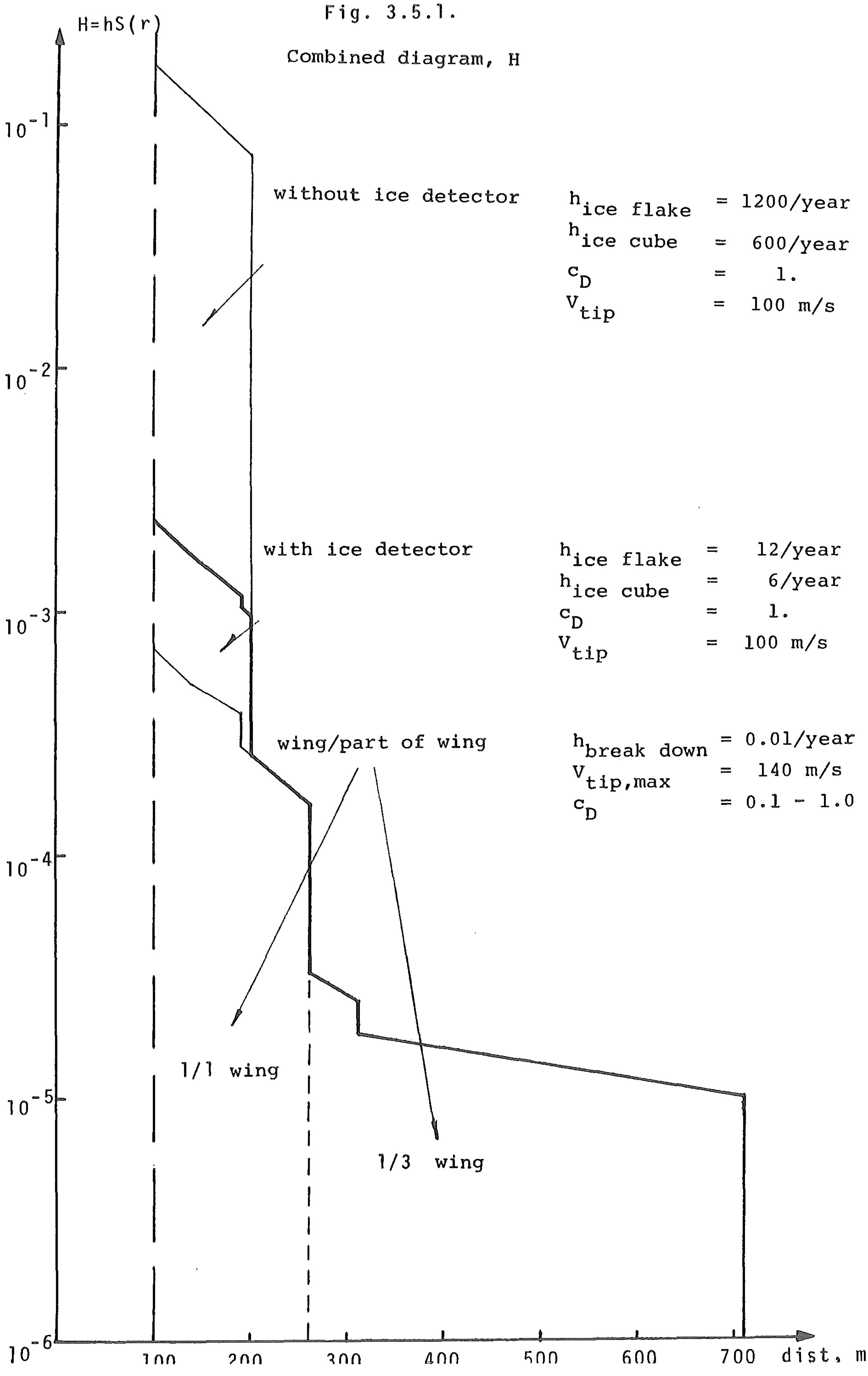
Fig. 3.4.11.



Maximum horizontal throw for 1/1 and 1/3 wing as function of c_D
800
700
600
500
400
300
200
100
dist, m
1/3 wing
1/1 wing
0.0
0.5
1.0
c_D

Fig. 3.5.1.

Combined diagram, H



DESIGN PROVISIONS FOR

WIND ENERGY SYSTEMS

LIGHTNING PROTECTION AND EMC

D. Jaeger

1. Introduction

Due to their height and place of location (flat, level terrain), wind energy systems can be prone to great danger of being struck by lightning.

This danger is two-fold:

a) Destruction of important mechanical parts, e.g. of the rotor blades
b) Interference with or damage of the electrical system/ electronics.

In addition, electromagnetic compatibility (EMC) aspects must be taken into account.

The following must be ensured:

a) The compatibility of all equipment installed in the wind energy system ("internal compatibility")
b) Compatibility with the electromagnetic environment ("external compatibility")

This paper is designed to give a survey of the danger anticipated due to lightning strokes and EMC, of possible solutions and of how they can be realized.

2. Survey of a wind energy system from the aspects of lightning protection and EMC examplified by MBB's wind energy system

The basic structure is illustrated in Fig.1. Basically, the system comprises the actual wind energy generator, three containers and the tower with the wind sensors.

The wind generator is composed of the rotor blade, the nacelle and the tower. The rotor blade is made of modern materials such as CFC and GFC. Extremely susceptible sensors and electronic measuring equipment are integrated.

The nacelle is made of steel plate. It accomodates the actual electrical generator as well as extremely susceptible control and regulating equipment.
Mainly cable installations and auxiliary equipment are located in the tower (e.g. lift).

The three containers are set up nearby. They consist of iron frames clad with aluminium. One container each includes the measuring electronics, the control and regulating electronics and the power current electrical system.
Sensors to determine important wind parameters are located in the other tower.

The following provide connections between the individual sub-systems:

a) High power current lines, control and measuring lines between the wind generator and the containers
b) Low voltage current and measuring lines between containers and tower with wind sensors.

3. Electromagnetic risk to wind energy systems due to thunderstorms

3.1 Electrical parameters

A survey is given in Fig.2.
The following may be expected:

a) Extremely high electrical field strength:
The amplitudes may reach up to some 100 KV/m in the case of near-by or direct hits (still approx. 1 KV/m 15 km from the storm cell accord. to (1)).
Since protecting measures are relatively simple, however, (Section 5.3.1), a more detailed explanation of the electrical parameter is dispensed with.

b) Lightning strokes:
Due to the concentration of electrical energy and the difficulty involved in protection measures, lightning strokes represent the actual problem.

3.2 Description of lightning

The danger due to lightning strokes depends on the probability of a hit as well as of the lightning parameters to be expected in the case of a hit.

A) Probability of a hit by lightning

This depends on:

a) the thunderstorm frequency in the area of installation, expressed by the hit probability a per year per square km (average value approx. 2.5 for North Germany).

b) the height h of the system
The following applies to heights below 8 - 100 m accord. to (2)

$$n \approx a \cdot h\ (160-h) \cdot \pi \cdot 10^{-4}\ (\%)$$

whereby

n = hit probability per year in %
a = hit probability per year per square km
h = height in m.

Thus curve I in Fig.3 results for a = 2.5 (North Germany).

As of a height of approx. 100 m, the triggering effect accord. to (2) occurs, which leads to the fact that objects about 15o m in height are already struck by lightning some 10 times annually.

All in all, curve II applies approximately to the hit probability per year for a single wind energy system. In the case of a series, the probability increases linearly with the number.

B) Anticipated lightning parameters

The most diverse forms of lightning may occur in the case of a hit, for instance the relatively wide positive earth lightning stroke, the negative earth stroke consisting sometimes of up to over twenty small successive single pulses, etc. As far as lightning protection is concerned, it has proved sufficient to describe lightning by the following parameters:

a) the peak current in [kA]
b) the rise in [kA/µsec]
c) the action integral $\int I^2 dt$ in [A^2 sec]
d) the charge in [C]

All parameters are expressed by probability distributions. Fig. 4 gives an idea of which values can be expected (derived from (3)).

3.3 Survey of the effects of lightning

This is illustrated in Fig.5.
Basically, a differentiation may be made between mechanical and electrical effects. The following mechanical effects, for instance, may occur:

a) destruction of important parts, e.g. of the rotor blade
b) melting of bearings
c) bending of rods, metal rims
d) material erosion
e) etc.

In particular $\int I^2\,dt$ can be considered as the cause of cases a) and b), which, multiplied by the resistance, gives the local conversion of the electrical energy to heat. It is above all magnetic forces which play a part in case c) (proportional to the peak current), in the case of d) the charge and $\int I^2\,dt$ are of interest.

The electrical effects may comprise a (temporary) interference or (permanent) damage of electrical system/electronics.

They may be caused by:

a) direct effect of the high magnetic fields occurring in the case of a stroke of lightning (Fig.6)

b) voltage peaks on lines due to
   - inductive couplings into cables (high magnetic fields)
   - galvanic couplings (poor grounding concept)
   - flash-overs (poor electric isolation).

The rise dI/dt and the peak current I_{max} are particularly responsible for these effects.

The electrical aspect of lightning protection is gaining increasingly in importance. This is due on the one hand to the fact that modern systems, including wind energy systems, are increasingly dependent on satisfactorily functioning electronics. On the other hand, modern electrical components have become more and more susceptible, as shown in Fig.7.

The destruction of diverse components in comparison with the energy of the lightning is illustrated. It is shown that the transistor, for instance, is about 1000 times more susceptible than the tubes and the IC, about 10 times more susceptible than the transistor. Utilizing the advantages inherent in modern components must therefore be balanced by increased expenditure for lightning protection.

4. Problems relating to Electromagnetic Compatibility in the case of wind energy systems

4.1 Task of EMC

A great deal of equipment is concentrated in modern wind energy systems over a small area which on the one hand generates or processes, respectively, very high electrical powers, but which on the other hand must be capable of receiving even the smallest electrical signals without any interference at all.
Furthermore, the systems may be located in an environment which is "contaminated" electromagneticallly by radio transmitters, radar equipment, etc. It is the task of EMC to ensure interference-free functioning in all circumstances.

4.2 Internal EMC

Fig.8 provides a survey of the problems connected with "internal EMC". A possible interference source (e.g. power converter, voltage transformer for emergency power supply) and a perhaps susceptible unit (regulator, computer unit, etc.) are represented. Both units are connected to each other galvanically (grounding concept!), inductively and capacitatively (cabling and shielding concept!) as well as electromagnetically (RF radiation).
The compatibility must be ensured by limiting the interference on the one hand, requiring a certain non-susceptibility on the other hand and optimum design of the "interfaces".

4.3 External EMC

Compatibility with the environment must be ensured. These activities can be limited in the case of the wind energy systems to:

a) Ensuring functioning in a certain RF environment. Fig.9 shows as a function of the distance which field strengths can be expected from typical RF sources.
Approx. 1 V/m can be assumed (depending on the type of equipment) as a guiding value for the susceptibility of equipment which is not especially protected.
It can be seen that either protective measures are necessary or that installation restrictions for the systems must be the case.

b) Checking the interfaces to the public mains system.
In this case voltage peaks are of importance which may enter or leave the system or public mains system.

5. Protective measures with respect to lightning protection and EMC

5.1 General

The preceding remarks have shown that wind energy systems are jeopardized by lightning strokes. This is especially true of very high systems. Lightning protection must be envisaged for small systems too, however. Although each individual system is less subject to being hit, they will probably be built in larger quantities, meaning that more frequent hits must be anticipated for this model. Since it is extremely difficult to implement lightning protection measures subsequently, such measures are already envisaged for wind energy systems during the development phase.
A certain minimum must furthermore be ensured with respect to electromagnetic radiation from outside (radio transmitters, radar equipment, etc.) in order to avoid too many restrictions at the site of installation of the systems.
A basic differentiation can be made between protective measures to prevent mechanical damage and such to prevent interference with or damage of the electrical system/electronics.

5.2 Protection against mechanical destruction as examplified by the MBB systems

In general, appropriate protective measures are absolutely indispensable, in particular when, as with the MBB systems, the advantages of modern CFC construction are to be utilized. This is a low-weight, high-strength material. Unfortunately it also features slight electrical conductivity, which is sufficient to "attract" lightning via field concentrations, but which is not enough to withstand lightning undamaged.

One problem when dimensioning the protective measures is which electrical parameter to take as a basis.
As shown by Fig.4, important lightning parameters are subject to extreme dispersions in the case of a hit. Since expenditure for lightning protection is not related linearly to the size of the parameter - costs accrue simply due to undertaking something - standard lightning as indicated in Fig.10 was taken as a basis for mechanical lightning protection for the MBB systems. This is synthetic lightning from (4), in compliance with which the protective measures for modern plastic aircraft are designed. More than 99 % of all risk are covered thereby.

The zones of the direct hit are of the greatest importance for lightning protection. These zones are determined in aircraft construction by means of extensive investigations. As far as wind energy systems are concerned, it can be said that lightning will almost certainly always hit the rotor blade. The blade tip is particularly endangered. The tower with the wind sensors can also be subject to a certain degree of danger. Lightning will almost never strike the containers.

Fig.11 provides a survey of the protective measures envisaged for the rotor blade.
The particularly endangered tip is coated with aluminium about 14 mm thick. As Fig.12 shows, a thinner material would be removed relatively soon due to lightning strokes. Furthermore, the blade tip is exchangeable.

The lightning current is conducted through metal rims (Al) with a section of 50 mm². Thus a sheet thickness of 0,5 mm is considered to be adequate.

The following problem is also of importance:
A lightning stroke is relatively stable in the case of a hit. It may last according to Fig.10 up to 1 sec, that is, the rotor blade rotates under the stroke, meaning that zones of the blade come into contact with the lightning which are not exposed to a direct hit. However, these amplitudes are weaker. Primarily the metallic edge of the rotor blade will be affected, which in this respect is dimensioned adequately. If the blade is inclined obliquely, the part under the blade tip may also be endangered. The upper third of the rotor blade was therefore clad with aluminium mesh (approx. 200 g/m², as known from measurements for aircraft programmes).

Despite the previously described protective measures, the CFC material used for the rotor blade still appears inadequately protected. An insulating plastic layer (GFC) lies between the CFC and the aluminium edge. When struck by lightning, a voltage of some 100 KV builds up between the metal, which can lead to uncontrolled flash-overs (Fig.13). In certain circumstances the very high local current concentration may damage the CFC. Since adequate insulation is absolutely impossible, the CFC is connected approx. every 50 cm with the metal edge. Current load is extremely low.

Further problems are anticipated with respect to conductance of the lightning current from the bearings. Bearings which do not need to execute a full revolution are bridged by bonding strips, the other by sliprings. The rotor bearing is especially critical - already slight damage can have a great effect, due to the high number of revolutions per minute and the long running time. The cross sections for the sliprings are determined by tests carried out together with the Army University in Neubiberg. The lightning current is further conducted additionally via the steel tower and a foundation earth electrode accord. to DIN 57185 (5).

5.3 Electrical protective measures

5.3.1 Survey of the protective measures

Fig. 7 has already shown that not enough importance can be attached to the electrical aspect of lightning protection. This applies particularly if the advantages inherent in modern electronics are to be exploited here, too.

Fig. 14 gives a survey of the interferences which act. The following shall be taken into account in the case of interference signals coming from outside:

- the electrical fields occuring in connection with thunderstorms
- the magnetic fields occuring in connection with lightning (direct and near hits)
- the interferences coupled galvanically (during lightning conductance) into the system
- the external high-frequency sources (EMC)
- the interferences coupled galvanically into and out of the lines to the public mains system (voltage peaks).

It is relatively simple to control the interfaces to the public mains system. Suitable lightning conductors are sufficient.

All other electrical parameters are coupled into the system via the structure. Fig.15 applies to coupling in of the fields and the electromagnetic radiation for metal strucures. This virtually means that

- the electrical fields are already relatively well shielded due to thin metal structures
- the magnetic fields represent the major problem, especially in the low frequency range
- coupling in RF radiation from the environment depends on the apertures available (number and size).

The interferences coupled in reach the susceptible electronics via the equipment cases and the interfaces between the units such as cabling, shielding and grounding. The interferences coming from other system equipment (internal EMC) also act on the above. In the main instance, the cabling, shielding and grounding act as the coupling. Fig.16 indicates the individual protective measures which are of relevance here. In this connection it is of importance that most of the measures are suitable with respect to lightning protection and external EMC as well as to ensuring internal EMC.

In order to ensure the compatibility of an electronics component in the system in all circumstances, the sum of all protective measures must ensure adequate decoupling between the interference signal occurring and the susceptibility.

5.3.2 Realization of the protective measures for MBB's wind energy systems

MBB's systems will in the following section be taken to illustrate how the above-mentioned protective measures can be transformed in practice.

A) Shielding due to the system structure

Large electrical and magnetic fields can be expected for the nacelle of the wind energy system (greatest vicinity to the rotor blade, discharging lightning currents). It is made of steel plate and thus exhibits extremely good attenuation.

The containers are made of aluminium sheet, but not with special reference to electrical attenuation. They are absolutely adequate for attenuating the electrical fields (Fig.15), for large magnetic fields are no longer anticipated due to the distance from the wind energy generator.

An attenuation of > 10 dB should be expected with respect to the external radiation sources. This means that, irrespective of the other protective measures, operating the system at distances of > 1000 m from customary radio and TV transmitters is possible.

B) Cable interfaces to the public mains system and between the subsystems of the wind energy system

Fig.17 provides a survey. All power lines to the outside and between the subsystems are switched against ground with conductors directly at the structure concerned. Depending on the type, signal circuits are protected additionally by a resistor and a Zener or Transzorb diode. This wirling prevents too large electric signals from being coupled via lines into the interior of the shielded zones. Protecting one wire costs about DM 20,--.

C) Equipment requirements

a) Non-susceptibility requirements

Absolute protection for all wind energy system equipment would be relatively expensive. Graded protective measures are therefore envisaged, depending on the importance of the equipment for the functioning of the system and with respect to the danger zone.
Fig.18 provides a survey.

The following classes of equipment can be defined:

- class I:
  measuring equipment in the rotor blade, positioned to the highest fields.
  Requirements:
  Leakless shielded case, no damage by cable-induced signals. Interference allowed.

The signals which shall be applied to all cable inputs and outputs of the equipment are shown in Fig.19. The curves are taken out of (6) and, after performing rough estimates, have proved to be suitable.

- class II:
  equipment at the rotor, all safety critical and at the wind tower:
  Additionally to class I no interference is allowed.

- class III:
  equipment in the nacelle (only safety critical units):
  Similar to class II, but shielding of the units is not so important (sielding of the nacelle!)

- class IV:
  equipment in containers (only safety critical):
  Because of the protection measures at system level only no interference is required when a signal interruption of < 50 µsec occurs.

- class V:
  all other equipment:
  No special requirements because of the protection measures at system level.

b) <u>Requirements concerning limiting the interferences emitted</u>

These requirements serve especially to assure internal EMC. It appears sufficient to detect the largest potential interference sources and to require for these a limitation of the interferences emitted (via lines and in the form of radiation) accord. to VDE 0871/0875/0877.

D) Cabling concept

The guidelines indicated in Fig.16 are complied with in order to prevent input couplings and overcouplings.
A symmetrical type of transmission is selected in the case of the particularly critical equipment in the rotor blade.

Particular attention is paid to spatially separate laying of line circuits exposed to interference and susceptible where greater distances play a part, for instance between the wind energy generator and containers (some 10 m). Separate shielded cable groups for power supply and signal lines are envisaged (Fig.17).

E) Shielding concept

A concept complying with Fig.20 is envisaged for connecting two pieces of equipment. The outer shield of the cable is connected to both housing grounds so as to be leakless (special connectors!). The inner shields are applied to signal ground (or in special cases likewise to case ground).

The connections between the subsystems (e.g. wind energy generator - container) will be implemented similarly.

F) Grounding concept

The grounding concept is designed in such a way that input couplings due to the lightning currents flowing over the structure and internal galvanic cross couplings are kept to a minimum.
A grounding concept similar to that in Fig.21 is envisaged.
It is based in principle on the separation of all grounds at equipment level (Fig.22) and joining critical grounds at one or a few points in the system.

6. Literature

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Working Group 3.4.4 / Power Energy Society, IEEE, May 1979

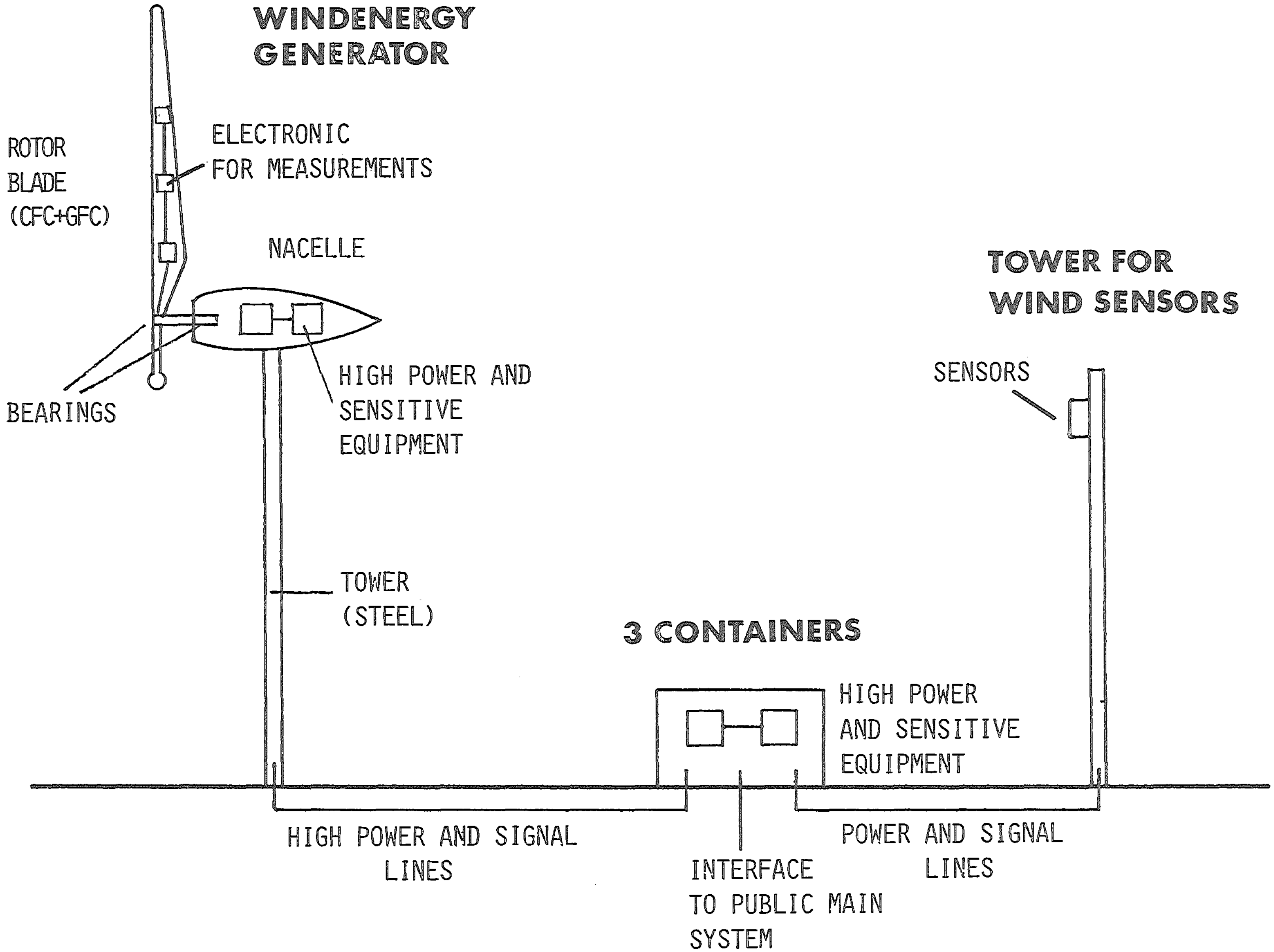


FIG.1:SURVEY OF A WIND ENERGY SYSTEM

1. ELECTRIC FIELDS

SOME 100 KV/M BEFORE LIGHTNING STROKE; SOME KV/M IN GREATER DISTANCES.

SIMPLE INTERFERENCE SUPPRESSING

2. LIGHTNING STROKE

THREAT DEPENDS ON:

- PROPABILITY OF HIT
- PARAMETERS OF LIGHTNING STROKE

MOST IMPORTANT PROBLEM BECAUSE OF HIGH CONCENTRATION OF ENERGY

FIG.2:SURVEY OF ELECTRIC THUNDERSTORM EFFECTS

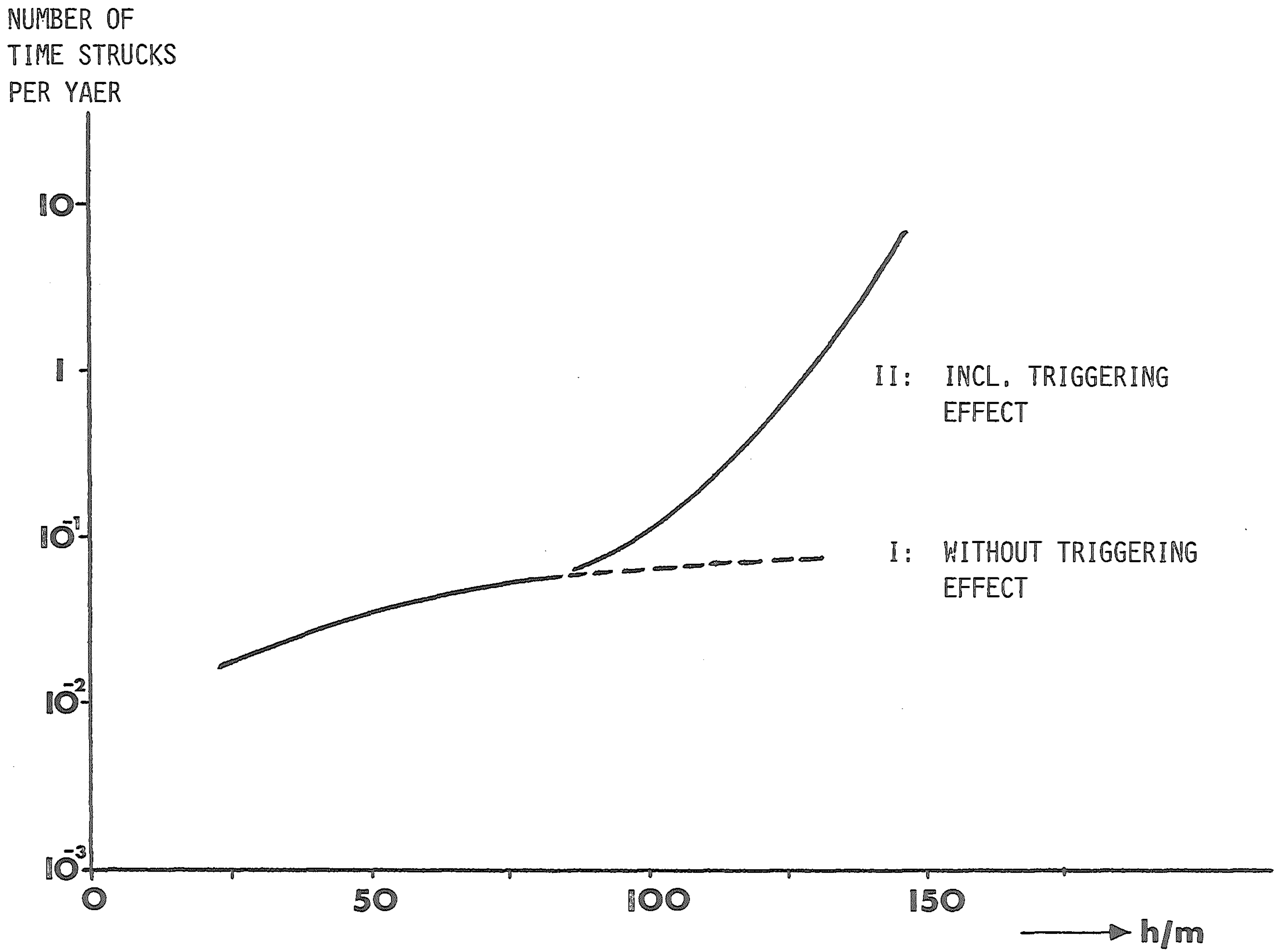


FIG.3:HIT PROBABILITY DEPENDING ON HEIGHT
(A=2,5)

	VALUE IN X% GREATER THAN				
	X=98%	X=90%	X=50%	X=10%	X= 2%
PEAK CURRENT (KA)	3	7	20	70	130
RATE OF CURRENT RISE (KA/μSEC)	5,5	9	20	60	100
ACTION INTEGRAL (A^2 SEC)	$6 \cdot 10^2$	$2{,}5 \cdot 10^3$	$2{,}5 \cdot 10^4$	$2{,}5 \cdot 10^5$	$8 \cdot 10^5$
CHARGE TRANSFER (C)	1	3	15	80	200

FIG.4:DISTRIBUTION OF IMPORTANT LIGHTNING PARAMETERS

1. MECHANICAL EFFECTS

- DESTRUCTION OF IMPORTANT COMPONENTS LIKE ROTORBLADE
- SMELTING OF BEARINGS
- DEFORMATION OF METALLIC BORDERS
- EROSION OF METALLICMATERIAL

RESPONSIBLE: $\int J^2 \, dT$, J_{MAX}, Q

2. ELECTRICAL EFFECTS

INTERFERENCE OR DESTRUCTION OF ELECTRIC UNITS BY:

- DIRECT EFFECT OF VERY HIGH MAGNETIC FIELDS
- SPIKES ON POWER AND SIGNAL LEADS CAUSED BY:
  - CAPACITIVE AND INDUCTIVE COUPLING INTO CABLES
  - CONDUCTIVE COUPLING (GROUNDING AND BONDING CONNECTIONS)
  - SPARK-OVER'S INTO CABLES

RESPONSIBLE: dJ/dT ; J_{MAX}

FIG.5:LIGHTNING EFFECTS

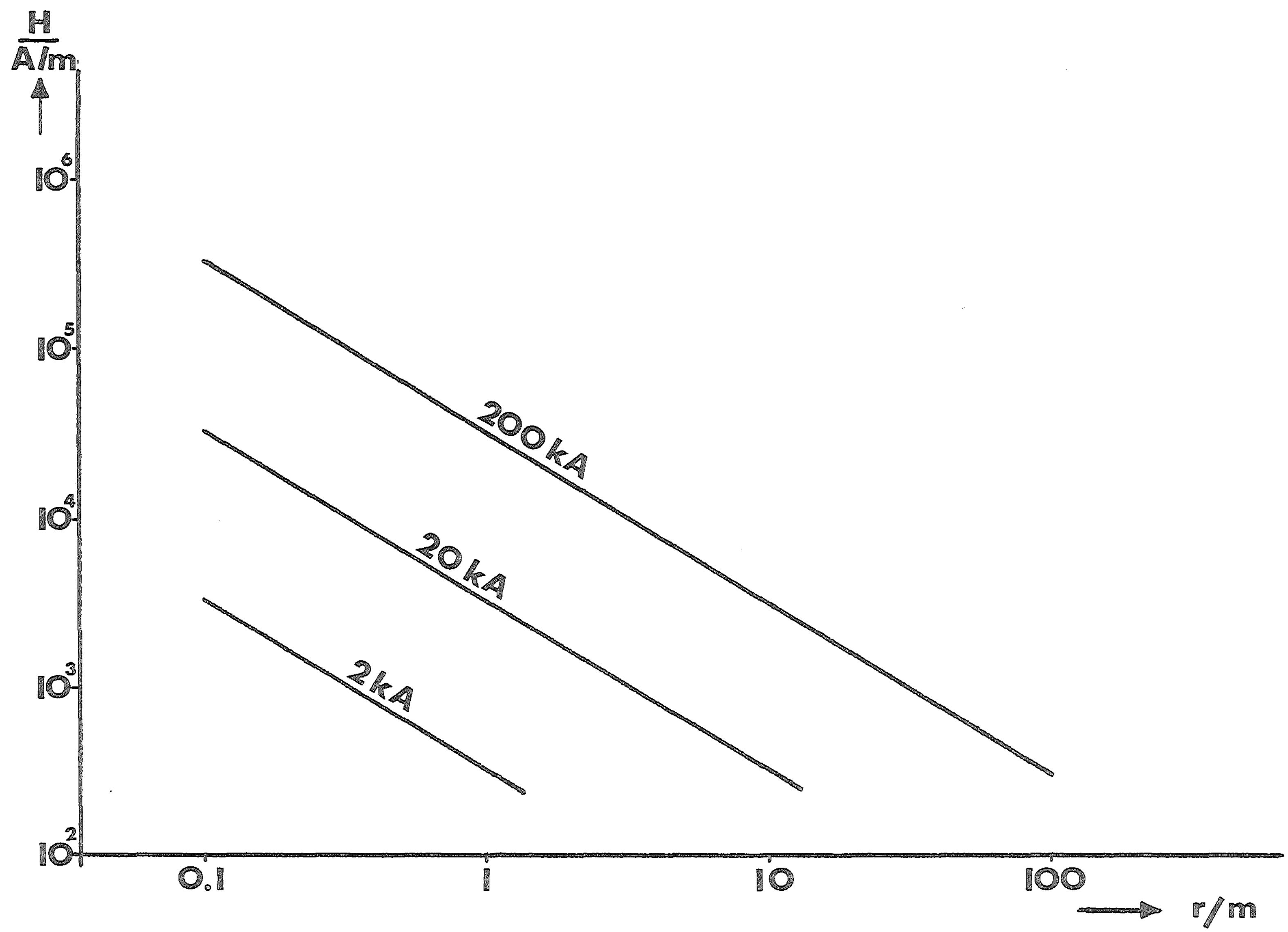


FIG.6:MAGNETIC FIELDS NEAR LIGHTNING STROKES

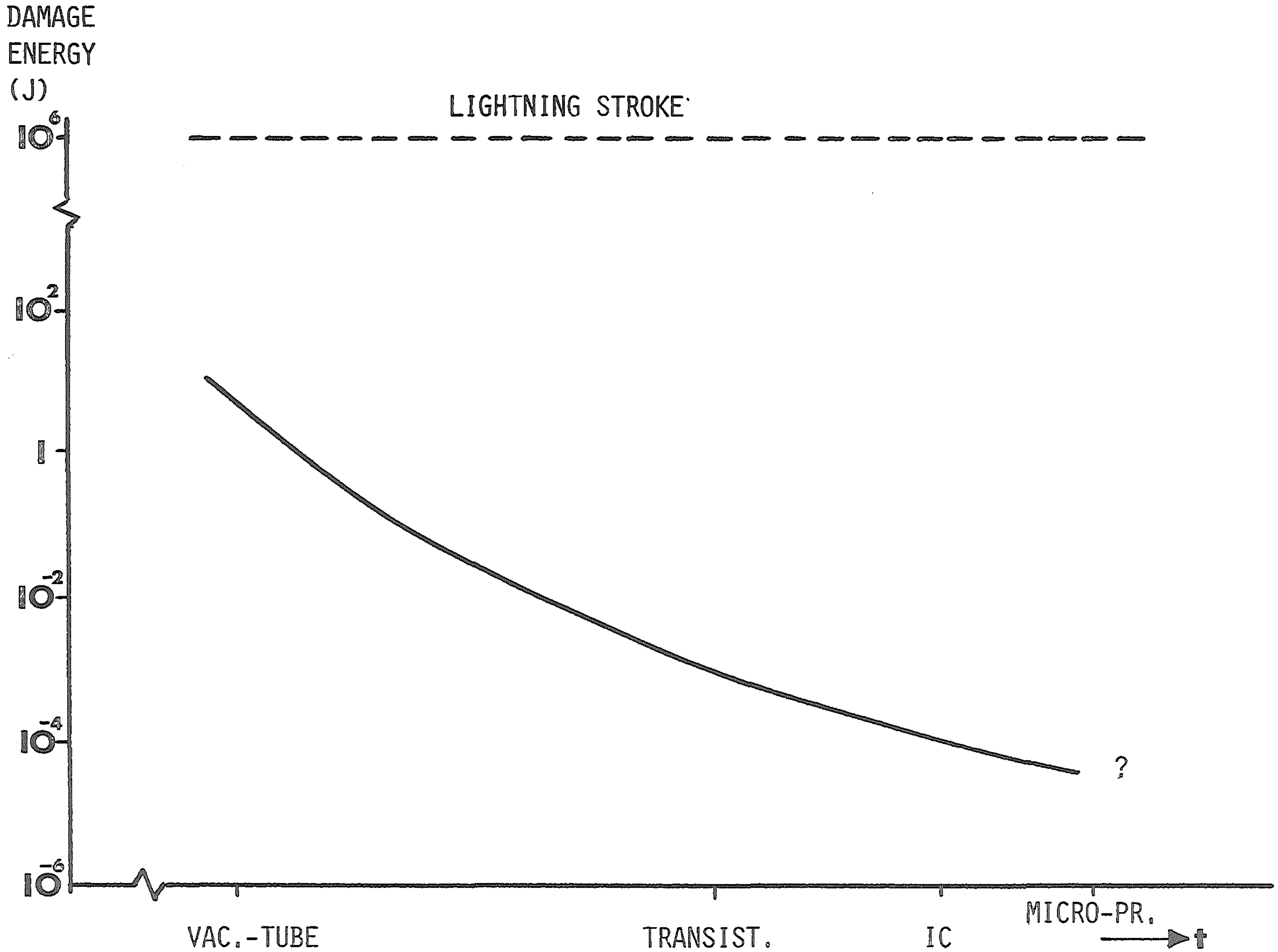


FIG.7: DAMAGE ENERGY OF TYPICAL COMPONENTS

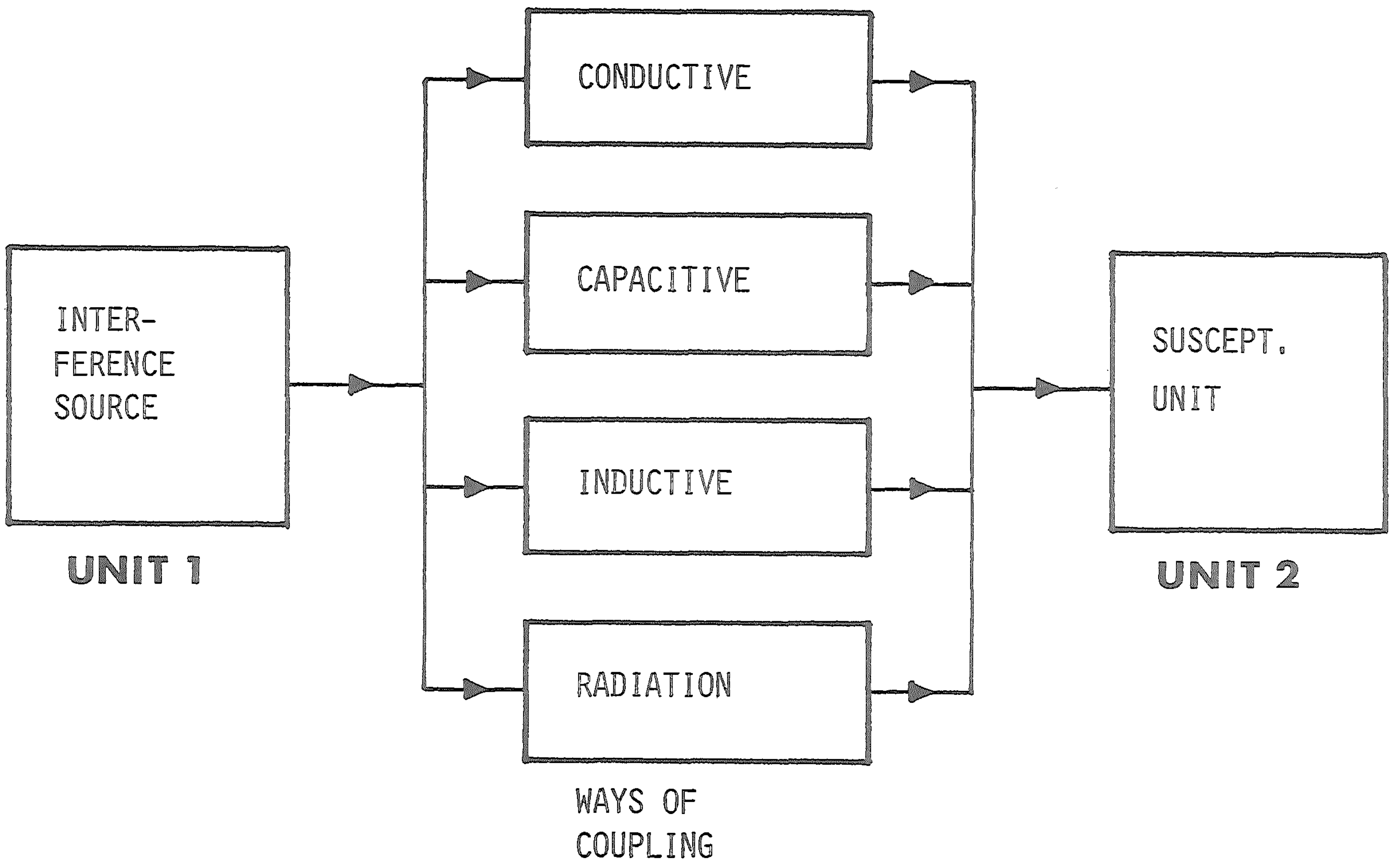


FIG.8:INTERNAL INTERFERENCE PROBLEMS

TYPICAL TRANSMITTERS	FIELD STRENGTH AT DISTANCES OF				
	100 M	300 M	1000 M	3000 M	10 000 M
LF , HF (500 KW , 0 DB)	39	13	3,9	1,3	0,39
HF (100 KW , 6 DB)	35	12	3,5	1,2	0,35
VHF (50 KW , 6 DB)	24	8	2,4	0,8	0,24
TELEVISION (50 KW , 6 DB)	24	8	2,4	0,8	0,24
RADAR (500 KW*, 30 DB)	1200 *	400 *	120 *	40 *	12 *

* PEAK

FIG.9:FIELD STRENGTH IN V/M PRODUCED BY TYPICAL TRANSMITTERS

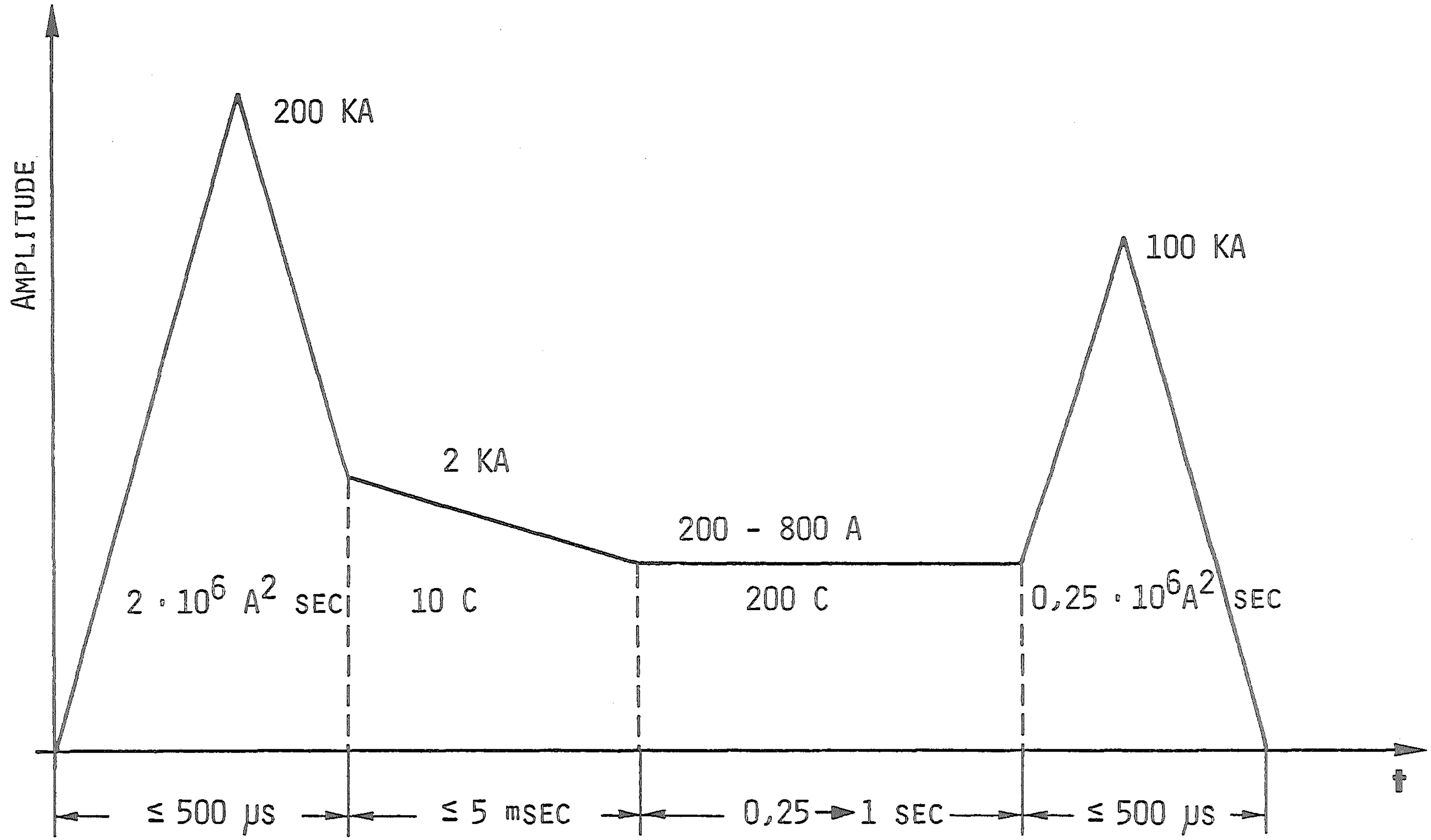


FIG. 10: NEW LIGHTNING TEST WAVE FORM

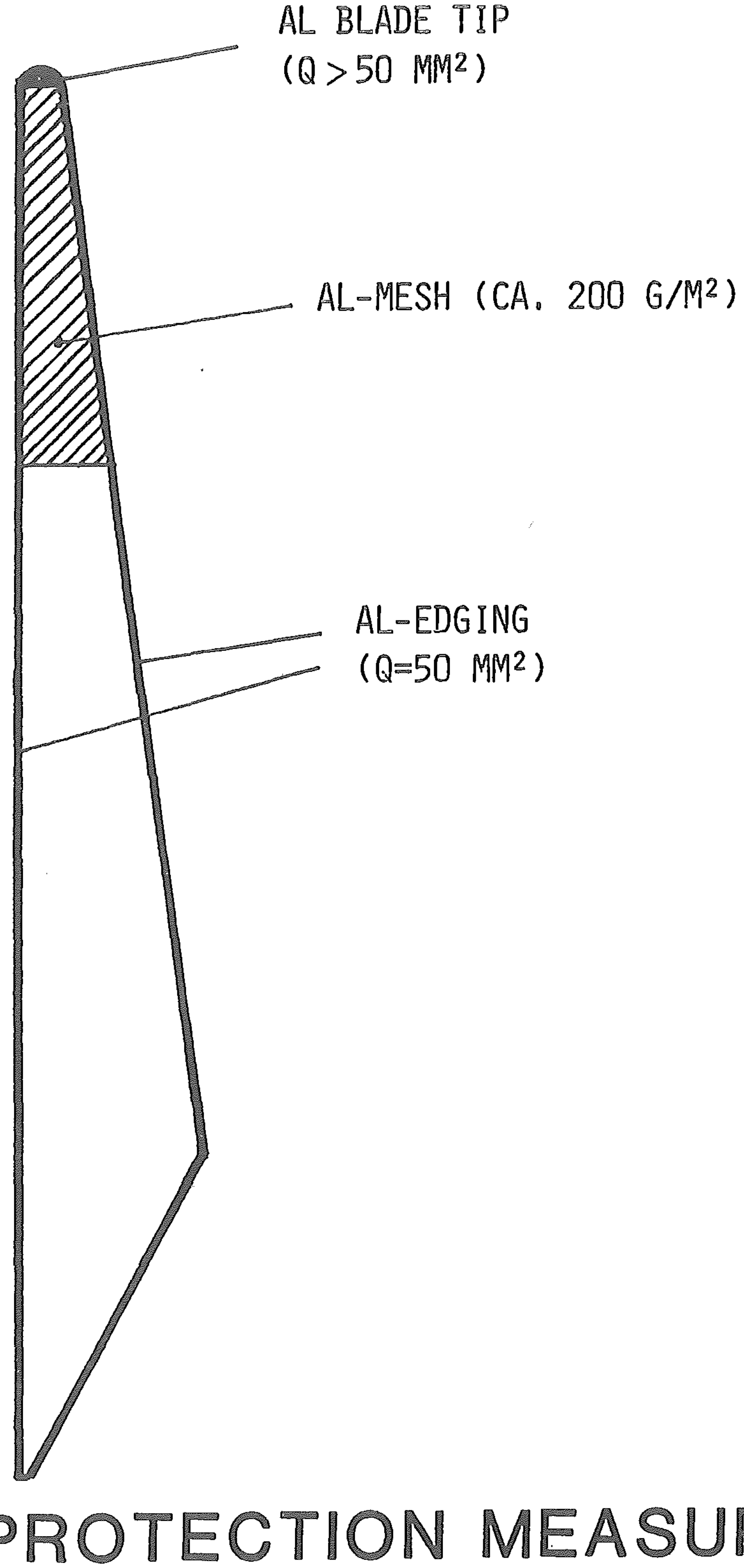
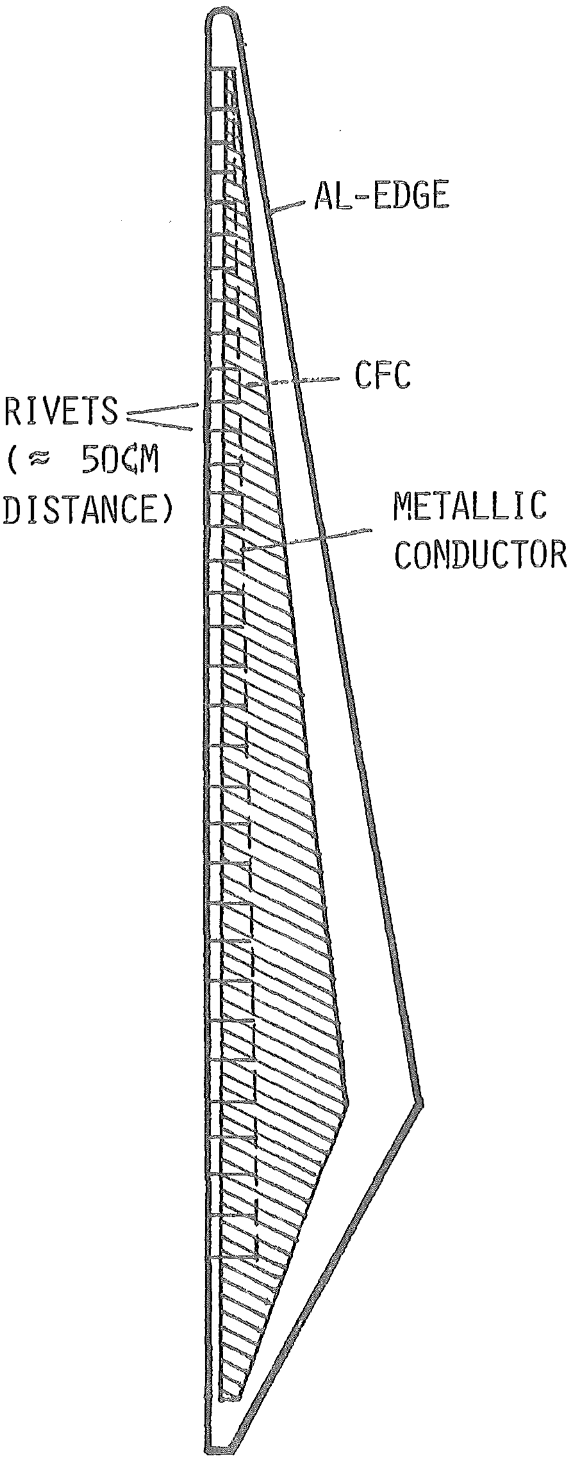
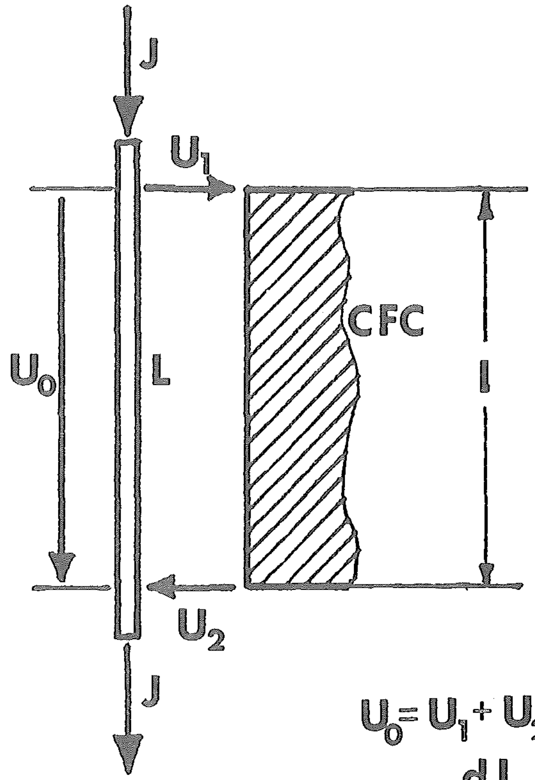


FIG. 11: PROTECTION MEASURES ROTOR BLADE (WITHOUT SPEC. MEAS. FOR CFC)

LIGHTNING PARAMETER		AREA OF EROSION IN MM^2		
CHARGE (C)	> IN%	D=0,5MM	D=1MM	D=2MM
15	50%	120	47	-
28	30%	245	81	-
50	20%	437	140	-
80	10%	700	219	-
200	2%	1750	538	80

FIG.12:EROSION OF THIN AL-MATERIAL CAUSED BY LIGHTNING





$$U_0 = U_1 + U_2 \quad (t \approx 0)$$

$$U_0 = L\,\frac{dJ}{dt}$$

EXAMPLE:
L=10M ≙ L ≈ 7μH;
FÜR 100KA/μSEC: $U_0 \approx 700$KV

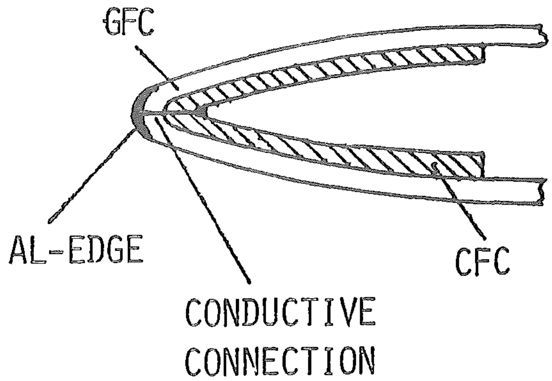


FIG. 13: SPECIAL PROTECTION MEASURES FOR CFC

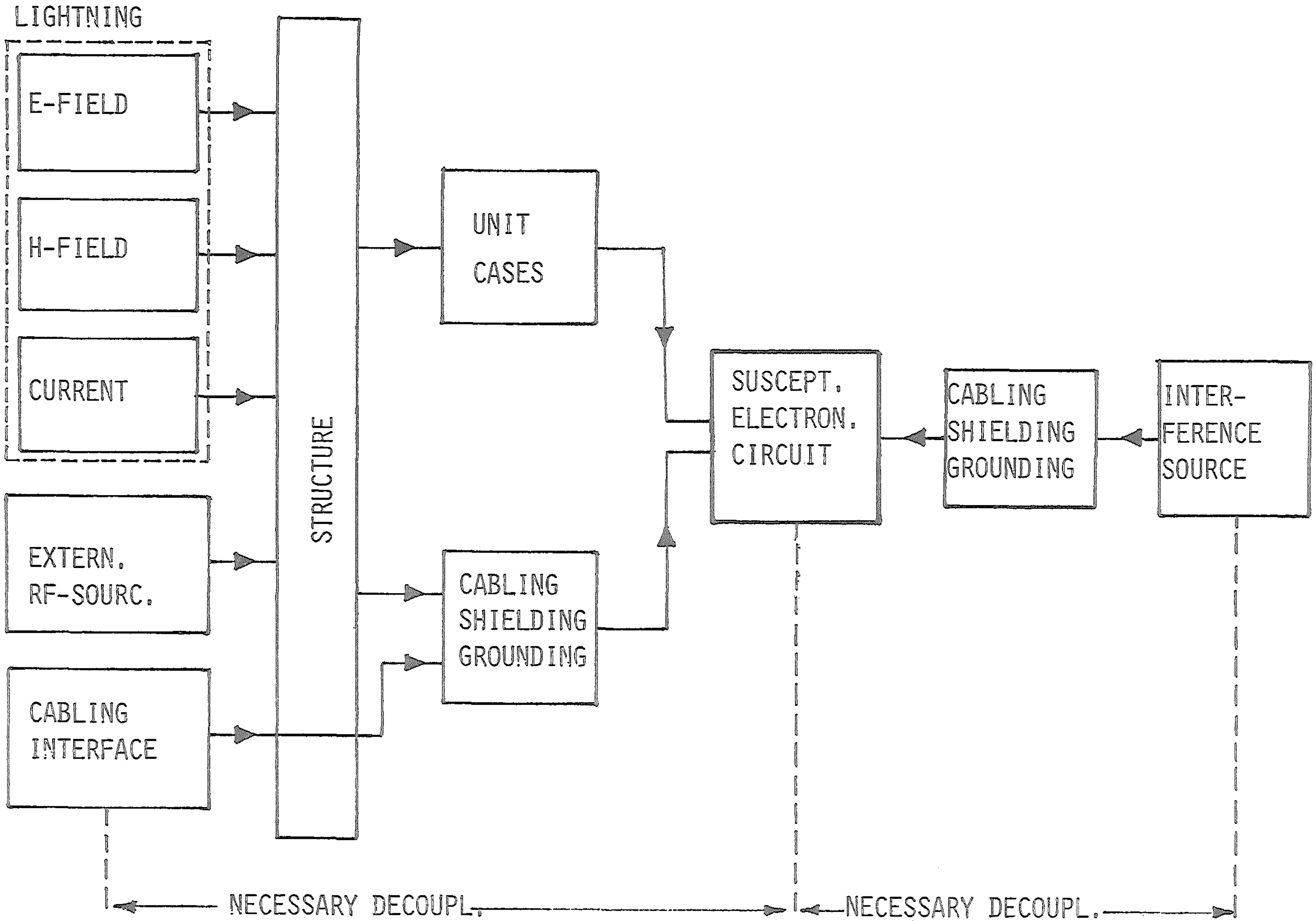


FIG.14:SURVEY OF COUPLING MECHANISM OF THE INTERFERENCE SIGNALS

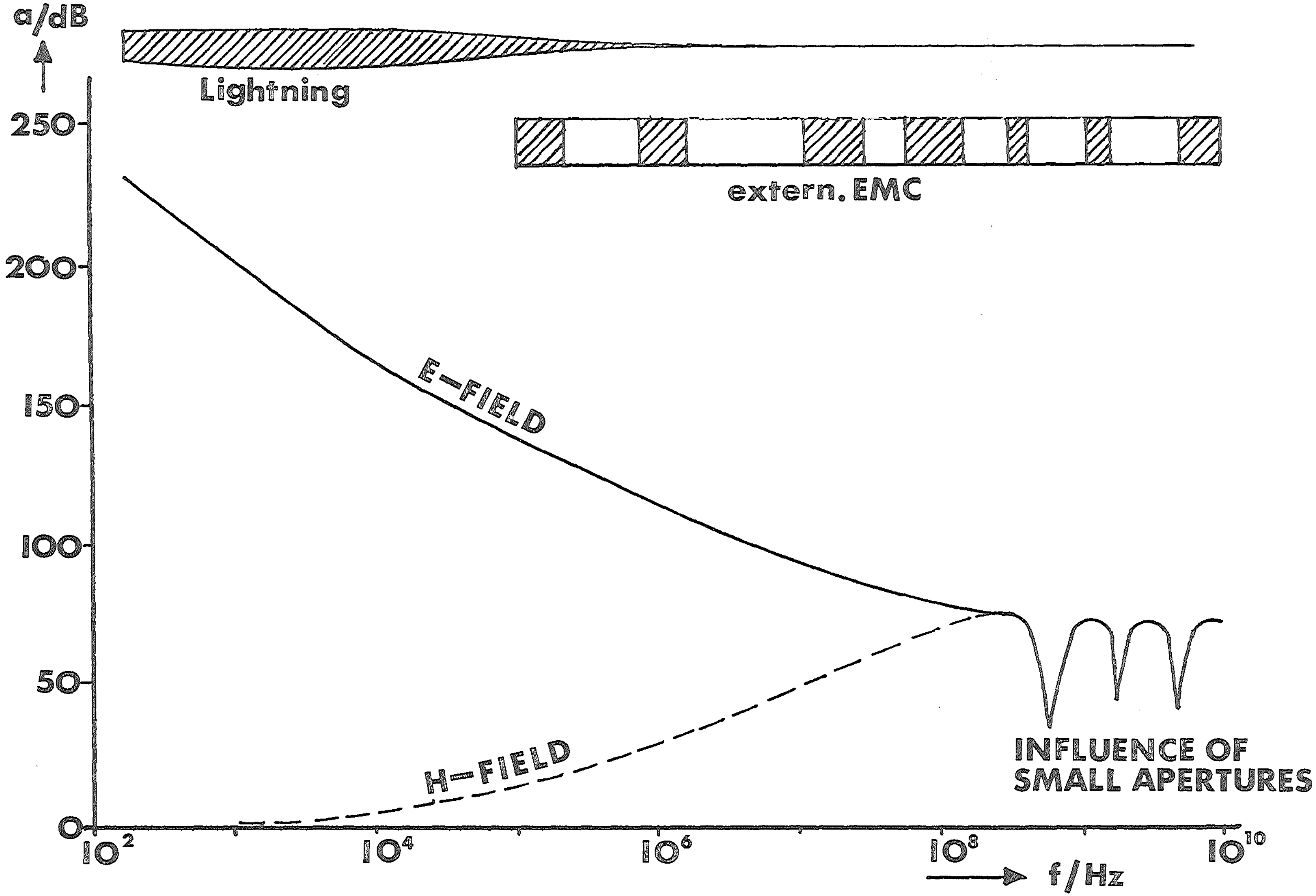


FIG. 15: ATTENUATION OF METALLIC STRUCTURES

1. ATTENUATION OF STRUCTURE

2. PROTECTION MEASURES AT THE INTERFACES TO THE OUTSIDE

3. USE OF INSUSCEPTIBLE EQUIPMENT
   - SHIELDED CASES
   - INSUSCEPTIBLE CABLE INTERFACES

4. EFFICIENT CABLING CONCEPT
   - TWISTING
   - SEPARATION OF SUSCEPTIBLE AND INSUSC. CABLES
   - FISHBONE CABLING

5. EFFICIENT SHIELDING CONCEPT
   - LEAKLESS SHIELDING

6. EFFICIENT GROUNDING CONCEPT
   - AVOIDANCE OF LOOPS AND CONDUCT. COUPLING

7. USE OF EQUIPMENT WITH LIMITATED EMITTED INTERFERENCE

FIG.16: SURVEY OF PROTECTION MEASURES FOR ELECTR. EQUIPMENT

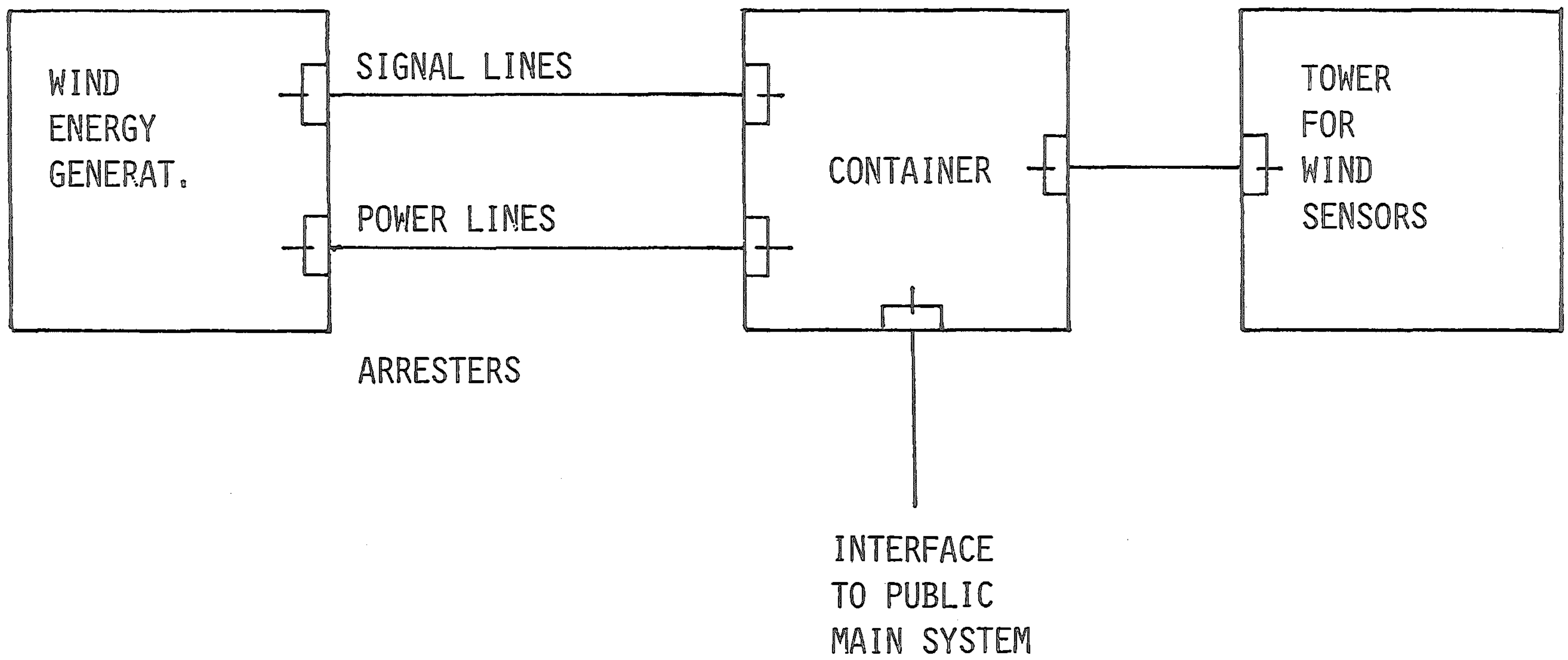


FIG. 17:PROT.MEASURES "CABLING INTERFACES"

EQUIPMENT		LEAKLESS SHIELDED CASE	NO DAMAGE (6KV/3KA)	NO INTERFERENCE (6KV/3KA)	NO INTERFERENCE, WHEN SIGNAL - INTERRUPT. $\leqslant$ 50μsec
I	MEASURING EQUIPMENT	X	X	–	–
II	EQUIPM. ROTOR-BLADE + WIND TOWER (SAFETY CRITICAL)	X	X	X	(X)
III	EQUIPM. IN NACELLE (SAFETY CRITICAL)	(X)	X	X	(X)
IV	EUQIPM. IN CONTAINERS (SAFETY CRITICAL)	(X)	–	–	X
V	ALL OTHER EQUIPMENT	(X)	–	–	–

FIG.18:REQUIREMENTS FOR ELECTR.EQUIPMENT

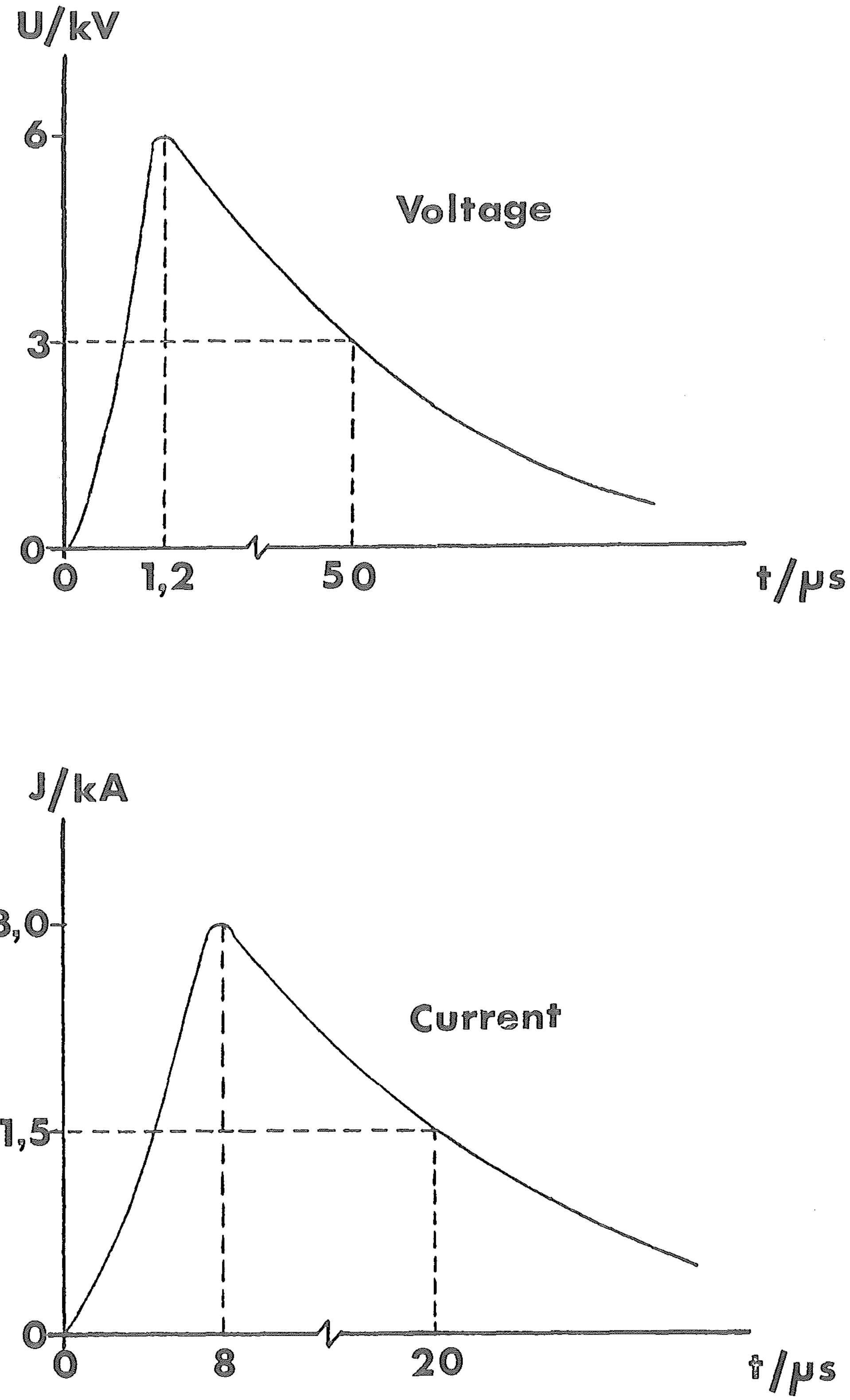


FIG. 19: LIGHTNING TEST SIGNALS FOR SIGNAL AND POWER LINES

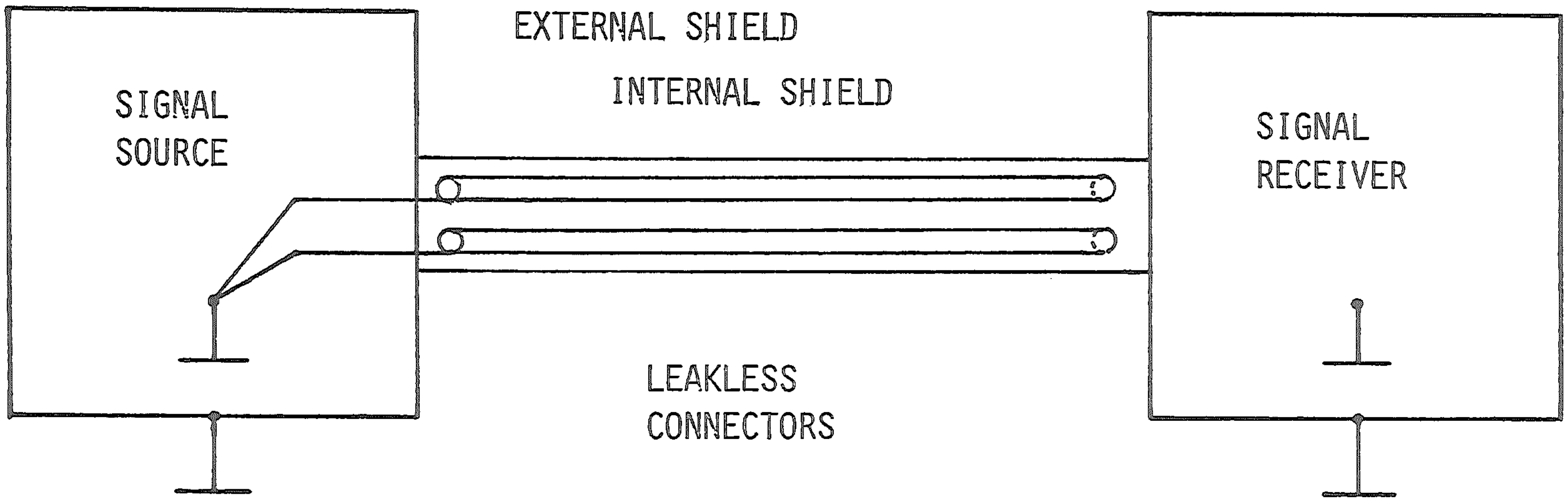


FIG.20:SHIELDING CONCEPT

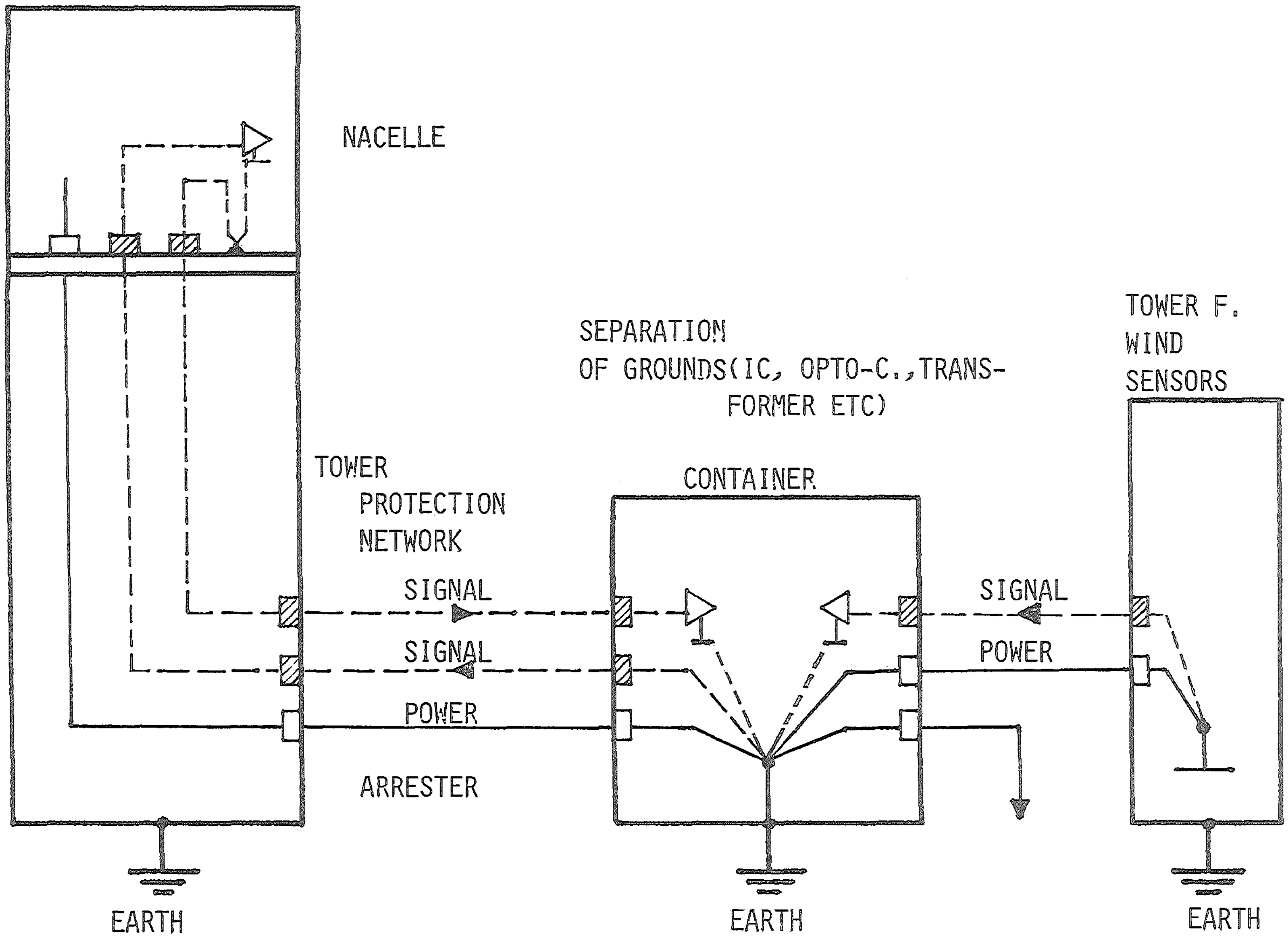


FIG.21:PRINCIPAL SYSTEM GROUNDING CONCEPT

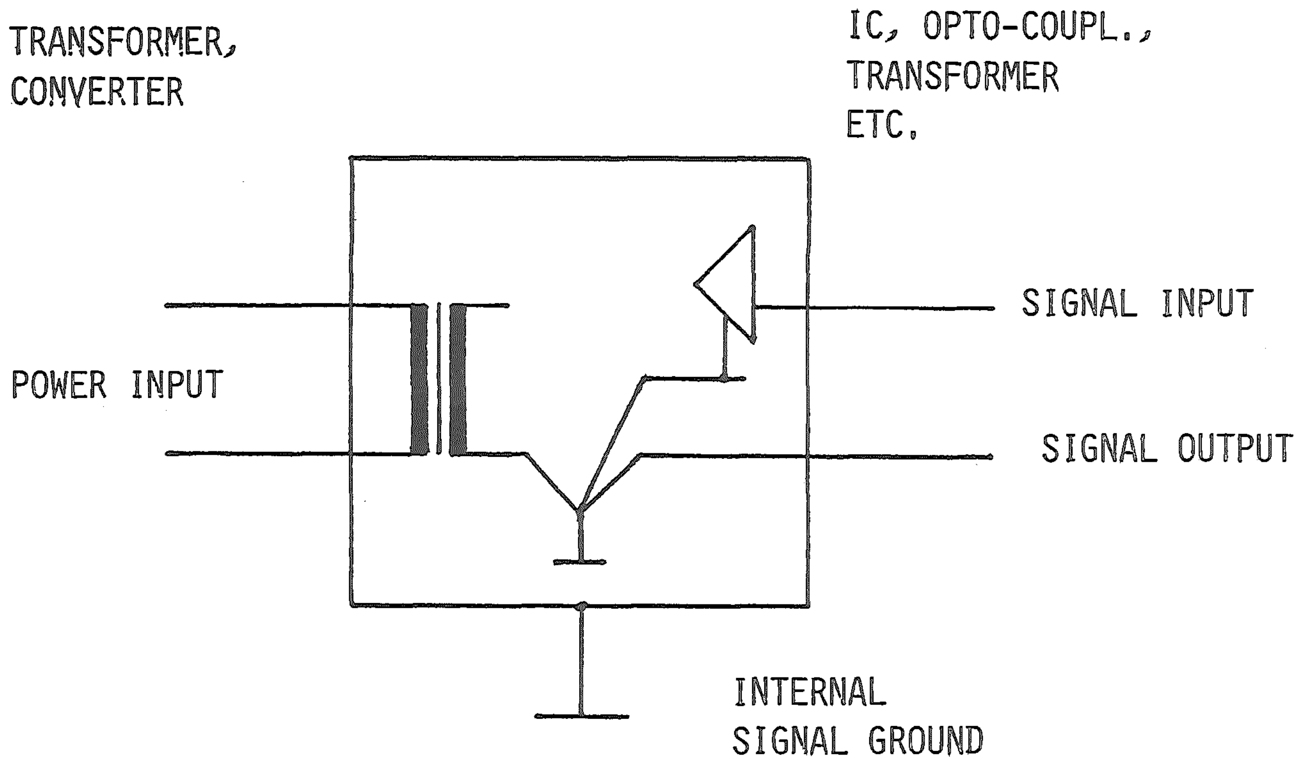


FIG.22:GROUNDING REQUIREMENTS FOR EQUIPMENT

"Environmental and Safety Aspects of the present LS/WECS"
IEA-Implementing Agreement for Co-operation in the Development of LS/WECS. 5. Expert Meeting 25./26.September Munich 1980

Rotational speed control by direct mechanical means.

by
F.X.Wortmann and S.Mickeler

The rotational speed control is also for a wind turbine a basic safety problem. The rated wind velocity of a windturbine is usually very low compared with stormy conditions. Therefore the speed governor, if it is considered as a safety device, should be capable to handle even the extreme wind velocities, independent of any cut-off boundaries. In the following some measurements will be reported with a rotor model (see Fig.1) which is controlled by a direct mechanical speed governor within a windvelocity range between one and fivetimes the rated wind velocity.

The direct mechanical control seems to be attractive due to its inherent reliability. The necessary masses for the fly-ball regulator are in the range of 5-10 % of the blade masses.

In order to hold the rotational speed constant the blade pitch angle may be changed by three different mechanical moments:

- the aerodynamic pitching moment of the blade
- the inertia moment of the blade (propeller moment) and/or
- the centrifugal moment of a classical speed governor.

The aerodynamic moment counterbalanced by a spring was not considered here as a unequivocal possibility to control the rotational speed. It depends not only on the dynamic head of the relative wind velocity because the pitch axis is not always in the neutral axis of the blade (e.g. due to different flapwise bending moments). The blade load then comes into play and it is hard to see that this method will work in a wide range of wind velocities and variable blade loads.

The propeller moment of the rotor has often been used as a speed governor working against a linear spring. Because the blade masses alone have the tendency to increase the rotational speed additional masses in form of a dumb-bell are usually added to correct the situation. (See Fig.2). This configuration has the advantage of simplicity. There is no influence of gravity and no additional bearings are necessary. On the other hand the controlling moments are small at small deviation angles φ (see Fig.2) and in Fig.3 it can be seen that the linear increase of the pitch moment is resticted to deviation angles below 30°.

Fig.3 compares the propeller moment and a linear spring moment for two different springs. At $\frac{\Omega}{\Omega_{krit}} > 1$ there exist different static equilibrium points, yielding a control function typical for a proportional regulator. Only in the range between $12 < \varphi < 20^{\circ}$ the moment of the spring S is nearly tangential to the propeller moment. In this small range the regulator has the so called integral or astatic behaviour: the "sensitivity" becomes very large and the rotational speed will be held constant.

Such a control device was tested with a small single bladed rotor model, with a diameter of 1,7 m. Because the wind tunnel can produce only 10 m/s as maximum velocity, the rated wind velocity v_o was set at 2 m/s. At this wind velocity the rotational speed is 5,5 rev/s and for higher speeds the regulator begins to act.

Fig.4 shows the static behaviour of the rotational speed for different wind velocities above the design speed. It should be mentioned that the spring S, which yields constant Ω between $1 < \frac{V}{V_o} < 1,5$, needs always a damper, otherwise the system is dynamically not stable. Due to the nonlinear behaviour of the propeller moment this type of regulator seems not to be able to hold the rotational speed constant over a wide range of wind velocities.

The third possibility to control the blade pitch is by the classical speed governor. Compared with the dumb-bell it needs some additional bearings. However there are also some advantages. The bearing point of the mass arm will now have some distance from the rotor axis. The centrifugal moment therefore can be increased at will and at the same time the range of linearity can be improved by starting in a position as in Fig.5.

With a corresponding linear spring moment it is now possible to obtain an integral regulator or an astatic control over a wider range of wind velocities.

The model used for the following results was the same as before, however the rotor model has now the freedom to flap and to pitch. When in Fig.5 the position of the regulator is frozen, any flapping motion yields a pitch motion. This coupling is well known as the δ_3 control. When the regulator works, is actuates the pitch angle via the lever arm. The aerodynamic moment and the propeller moment of this model are low compared with the regulator moment.

Fig.5 and 6 give the typical details of such an arrangement. Fig.7 compares the centrifugal moments with the linear spring moments for three different springs. Fig.8 shows the effect of these springs on the rotational speed for wind velocities between one and five times the rated wind speed under static conditions. The dynamic behaviour is illustrated in Fig.9. A certain damping is necessary to certify a stable regulation.

The last two figures 10 and 11 are obtained with a slightly improved version. The regulator in Fig.5 and 6 has only one mass which is influenced by gravity. This influence can easily be compensated by a second mass on the opposite side. Fig.10 shows the rotational speed, the flap angle, the regulator position and the power output as function of the wind velocity. Fig.11 indicates the effect of a load variation on the rotational speed, when the wind velocity is held constant. It can be seen that the classical speed governor is well be able to control the rotational speed of a windturbine for a wide range of wind velocities within tolerable boundaries at the expense of an additional mass 5-10 % of the blade mass.

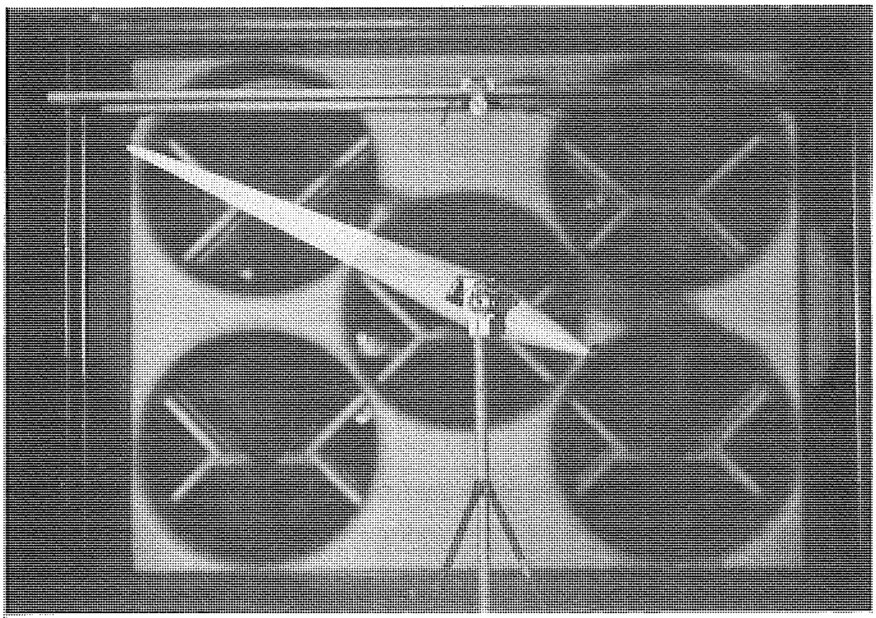


Fig.1 Single bladed rotor model in a low speed wind tunnel

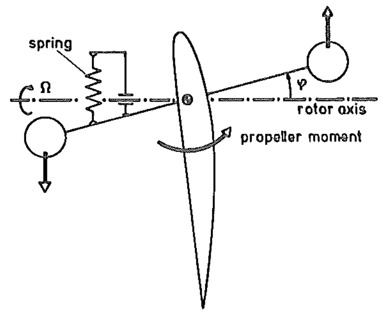


Fig. 2 Propeller moment acting against a spring

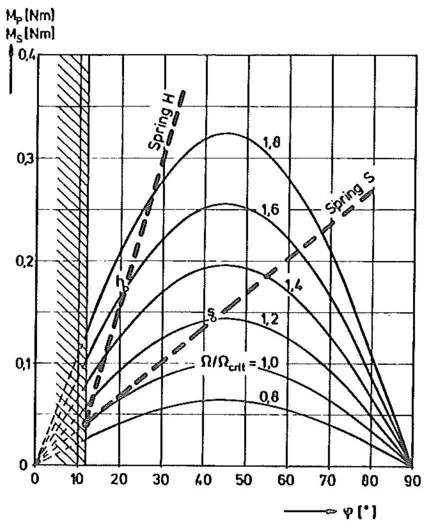


Fig. 3 Characteristics of spring and of propeller moment

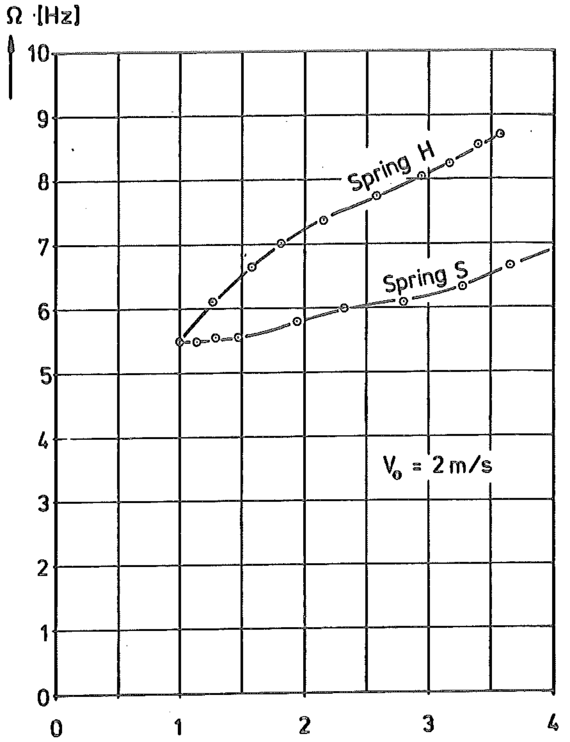


Fig. 4
Rotational speed controlled by propeller moment. Steady flow.

Fig.5 Classical speed governor with dampers

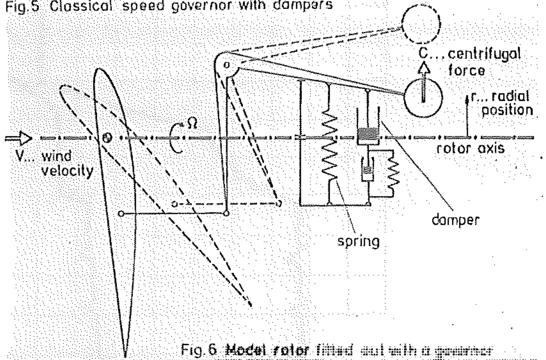
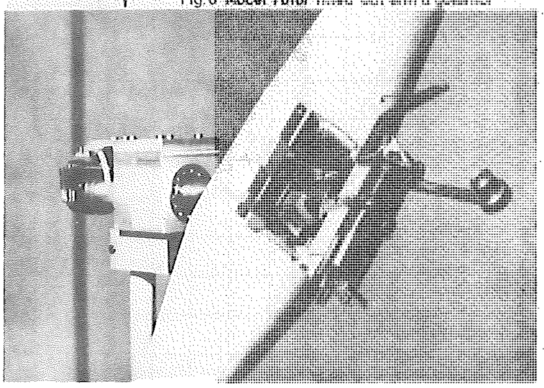


Fig. 6 Model rotor fitted out with a governor



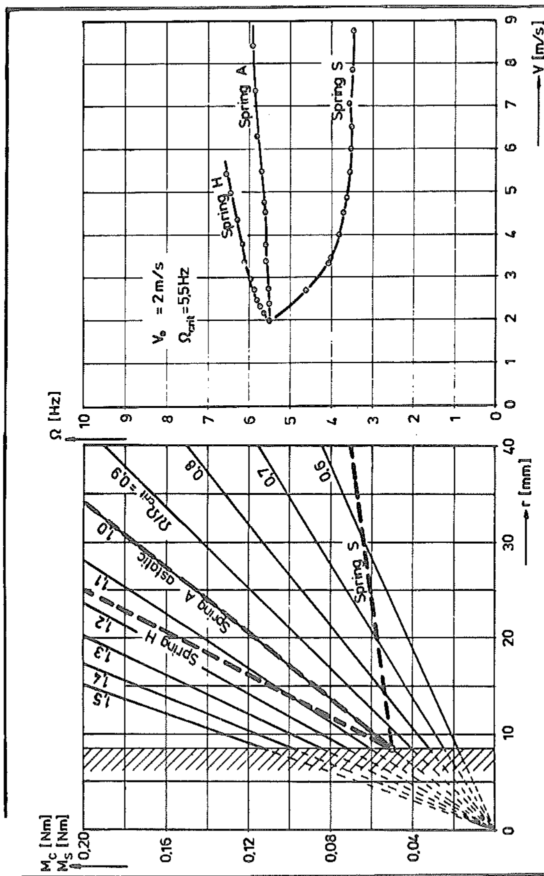


Fig.7 Spring characteristics and the characteristic of the model governor

Fig.8 Rotational speed controlled by the model governor. Steady flow.

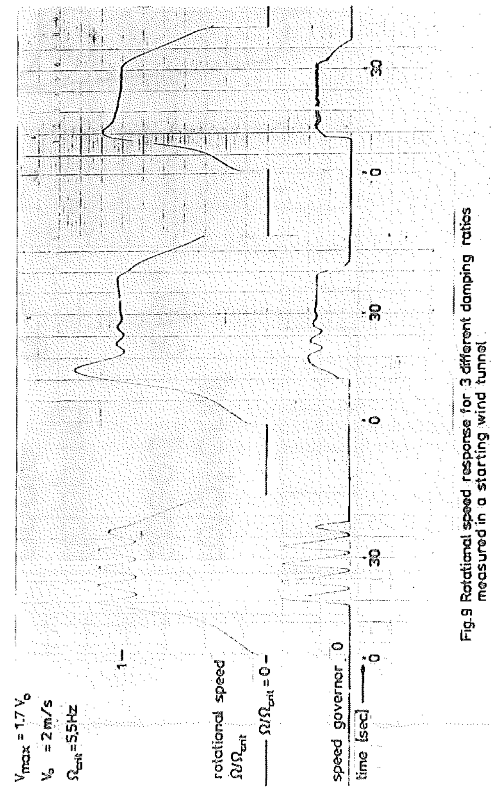


Fig.9 Rotational speed response for 3 different damping ratios measured in a starting wind tunnel

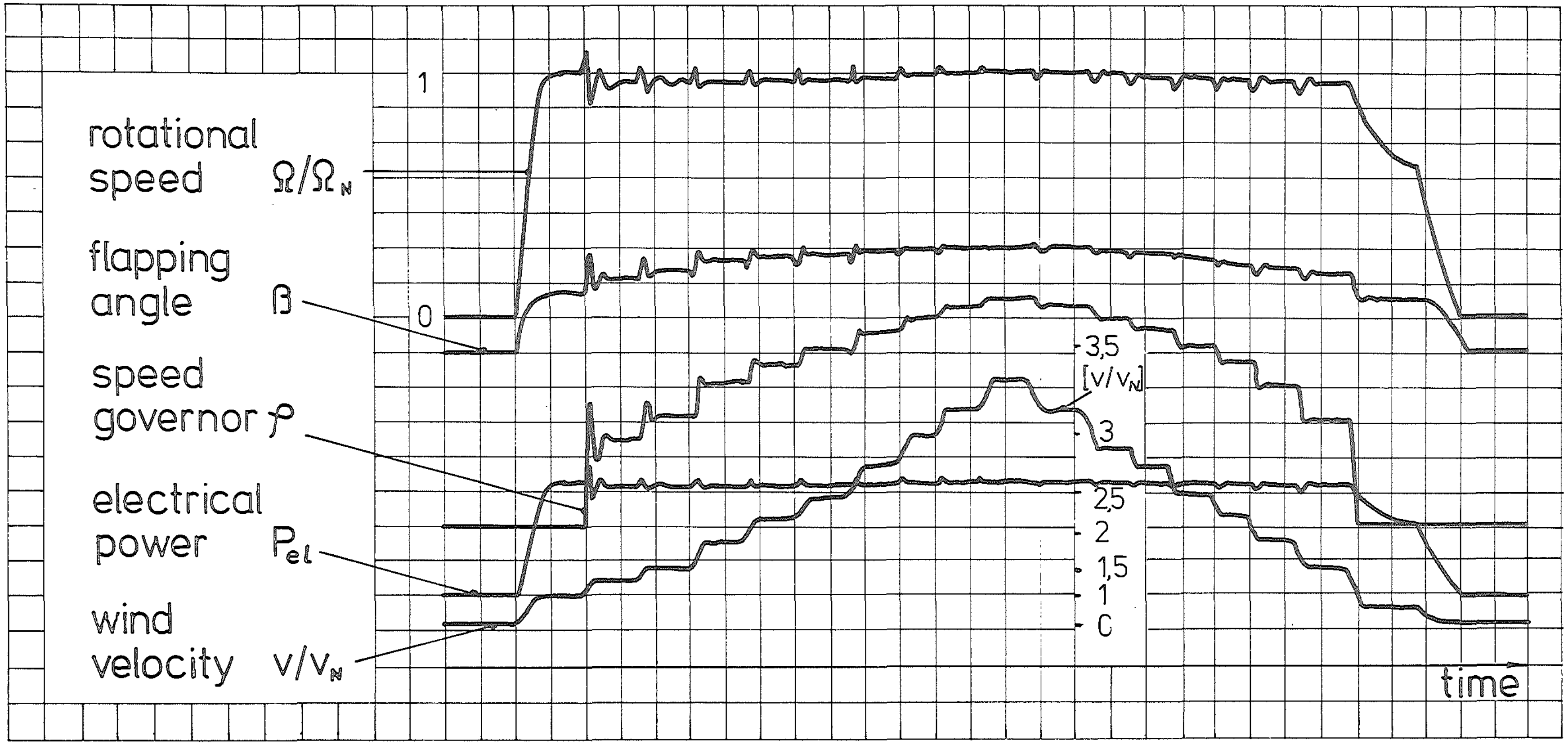


Fig. 10 Rotational speed and wind variation

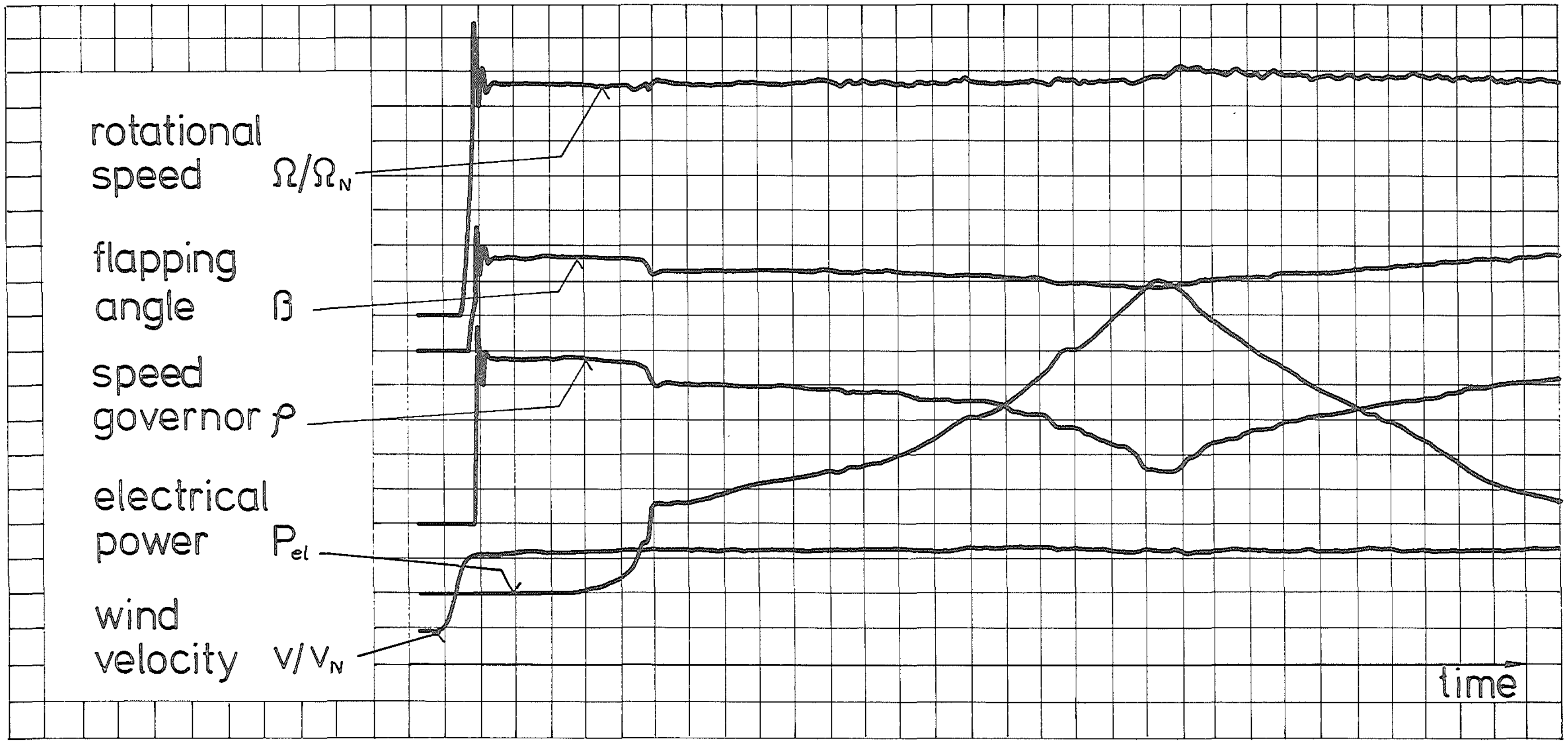


Fig. 11 Rotational speed and load variation

G R O W I A N   S A F E T Y   C O N C E P T

by

E. Hau / G. Huß

C O N T E N T S

I. INTRODUCTION

The design of the GROWIAN large wind energy plant is dictated to a considerable extent by safety considerations, and in view of the fact that there have been no binding safety specifications so far for such plants, the designer is often faced with difficult decisions when determining design features and systems. Compromises are inevitable and these must on the one hand guarantee the necessary margin of safety, but on the other avoid making the plant uneconomic from the start by designing it too big or overloading it with redundant systems.

The following comments are an attempt to provide a survey of the most fundamental safety measures in the specific case of the GROWIAN system.

Two aspects come particularly to the fore:

- safety at the structure design
- the functional safety system which is to prevent the overspeed of the rotor or its retardation in emergencies.

The safety concept of GROWIAN is based primarily on the reliability of the underlying assumptions and design arguments in these two areas.

II. SAFETY CONSIDERATIONS IN THE STRUCTURE DESIGN

The first condition for the safe operation of a wind energy plant is that the basic components of the structure should be sufficiently strong. The most important group of problems to confront the designer in this connection are the "definition" of the correct load cases together with the stresses resulting from these, and the availability of reliable constructing standards when he determines the allowable material stresses in order to correctly dimension the structure.

1. Load Cases

Of those loads to which the wind energy plant is exposed, by far the most important are naturally those resulting from the wind itself.

From the aspect of safety, two questions must be asked:

- Is the case of maximum load from wind, which can be expected on occasions over the service life of the plant, covered by the calculated examples of loads, so that the possibility of abrupt failure can be eliminated?
- Do the loads beneath the maximum load occur with the statistically correct frequency so that fatigue breaks will be avoided?

These are, in the first instance, questions for the meteorologist, but to extract from these real and very complex load situations manageable idealised "load cases" and to define them clearly presents a problem that can in no way be solved from the meteorological aspect alone. Rather, the reaction of the rotor to the real loads from the wind is an engineering problem, the solution of which has at least as great an influence on the definition of the correct load cases as the meteorological conditions. The discussion of the load cases on the basis of which GROWIAN was designed would bear no relation whatsoever to the framework described here. Table 1 therefore is designed to give only a qualitative impression of the kind of load cases on which the structure design is based.

Tab. 1

L o a d C a s e s

- Normal Operation with windspeeds of 6 - 24 m/s
  load cycles up to 10^8

- Gusts with wind speeds up to 40 m/s
  load cycles 50 - 10^4

- Locked rotor with wind speeds up to 60 m/s

- Rotor braking procedures
  (with simultaneous wind gusts)

2. Applicable constructing standards

The specifications on which construction is based have a decisive importance as they determine the safety of the construction elements.

In these specifications, the allowable stress values for the material and the connecting elements (particularly those relating to welds) are determined dependently of the kind of stress occurring.

One soon discovers that there have been no specific agreements so far relating to wind energy plants, which means that there is a very large area within which the designer is called upon to use his judgement as to which of the available DIN or other specifications (e.g. from aircrafts) he should use as a guide for his designs.

Table 2 contains a list of constructing standards which were used as a basis for the dimensioning of steel components for GROWIAN, particularly for the steel spar of the rotor blades. Most use was made of the crane constructing standard DIN 15018.

Tab. 2

Applicable Constructing Standards

DIN 15018

"Kranbau-Normen" (Basis)

DIN 4100

"Geschweißte Stahlbauten"

DIN 4133

"Schornsteine aus Stahl"

DV 848 (Deutsche Bundesbahn)

"Vorschriften für geschweißte Eisenbahnbrücken"

III. FUNCTIONAL SAFETY SYSTEMS

1. Speed-reducing procedures for the rotor

In addition to the safety considerations with respect to the structural components in a complex system such as a large wind energy plant, questions of safety arise which concern the actual operation of the plant.

Among the many safety systems which concern the plant's operation, the most important is that preventing the overspeed of the rotor, which can cause uncontrolled power output and overload of the plant.

In the case of GROWIAN, the maximum rotor speed is restricted to 1.3 times the nominal rotational speed.

In normal operation, a further increase in rotational speed is prevented by the power control system, i.e. by regulating the rotor blade pitch angle.

In view of the fact that there would be dangerous results if the maximum permissible speed were exceeded to any considerable degree, it must be absolutely certain that this restriction of speed is guaranteed even if one of the many conceivable defects should occur.

Various safety systems are available for this purpose which, in one way or another, guarantee that the rotor speed will be reduced dependently of the degree of danger and of the kind of defect. Table 3 gives a summary of the planned speed-reducing procedures for the rotor. Fig. 1 shows the course of those procedures through time.

Tab. 3

Speed Reducing Procedures for the Rotor

1. Normal Shutdown Procedure

   by the electrical blade pitch motor;
   pitch rate controlled by computer

2. Safety Shutdown Procedure

   (Failure in the computer or control system)
   blade feathering by electrical blade pitch motor with
   constant pitch rate of 4 deg/sec.

3. Emergency Shutdown Procedure

   (Failure of the total electric system)
   blade feathering by an additional hydraulic emergency system
   together with the mechanical rotor brake

   These systems are activated :

   a) "electrically" at rotor overspeed $n = 1.17\ n_{rated}$

   b) by a centrifugal mechanism at rotor overspeed $n = 1.20\ n_{rated}$

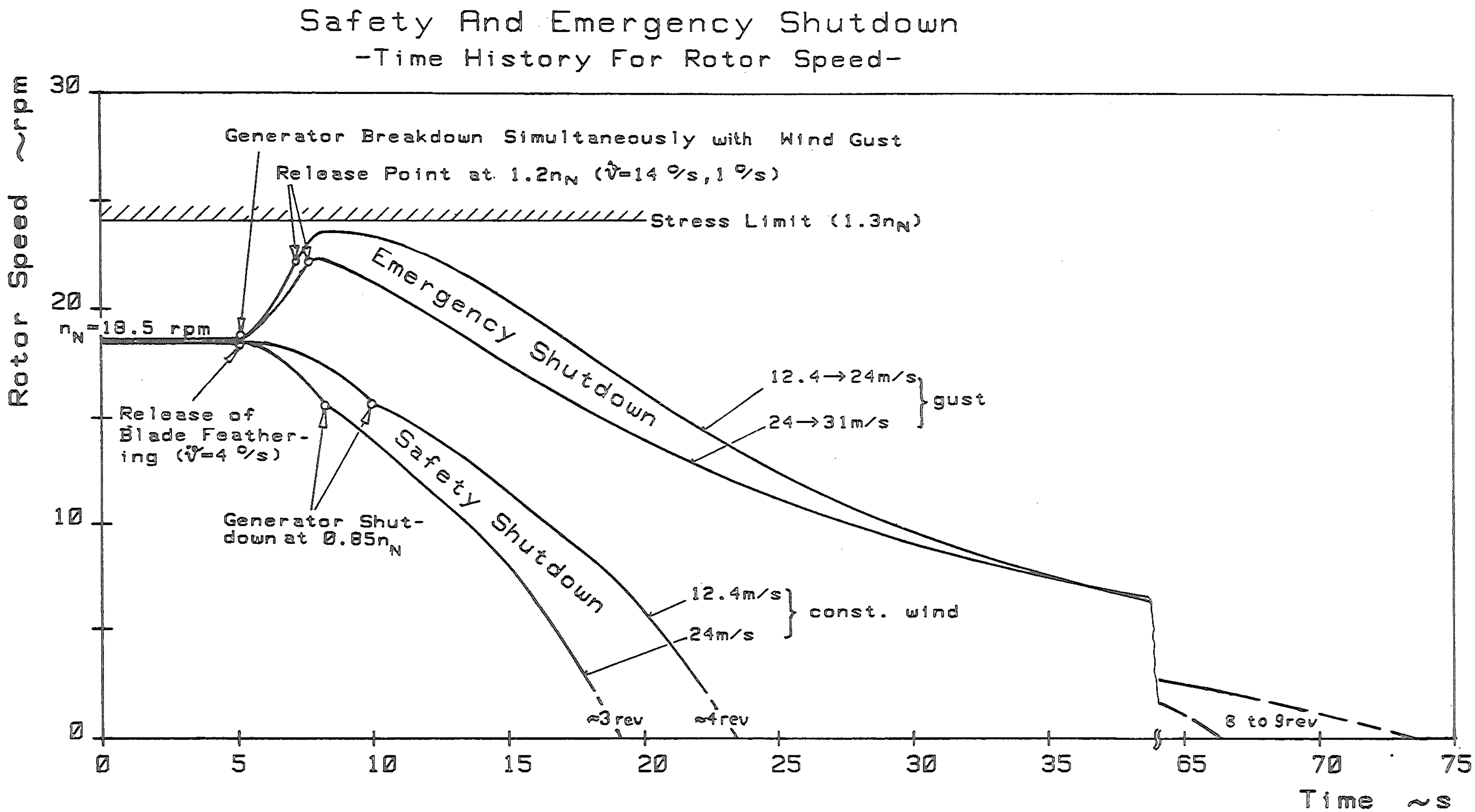


Abb. 1: Safety and Emergency Shutdown

2. Hydraulic emergency cut-off system

The hydraulic emergency cut-off system is the most important of the safety systems designed to reduce the rotor speed. This mechanism is designed this way that, if the electrical supply fails completely, an additional hydraulic system is activated automatically to set the blade pitch angle. This system turns the rotor blades to the feathering position and thus, together with the existing mechanical motor brake (Fig. 2), brings the rotor to a stop.

The basic functioning of this system is shown in Figs. 3 and 4.

In this, hydraulic cylinders fed from a high pressure vessel are arranged parallel to the blade pitch spindle. These cylinders can displace the whole pitch mechanism (drive motor, spindle and crosshead) which has a slide bearing, in such a way that this movement becomes one in which the blades are set in the feathering position.

This procedure triggered by a valve is intended to be doubly redundant. On the one hand, as already mentioned, because the current is cut off when overspeed reaches approx. 1.17 x the nominal speed, and on the other because of a mechanical centrifugal-force mechanism operating at 1.2 x the nominal speed.

An alternative to the hydraulic emergency cut-off system is to be found in a mechanism which uses the rotation of the rotors to turn the blades into the feathering position. This, in principle simple, solution would have led, however, to unjustifiably high design costs when applied to the large dimensions of the GROWIAN pendulum hub. This idea was therefore rejected in favour of the hydraulic system.

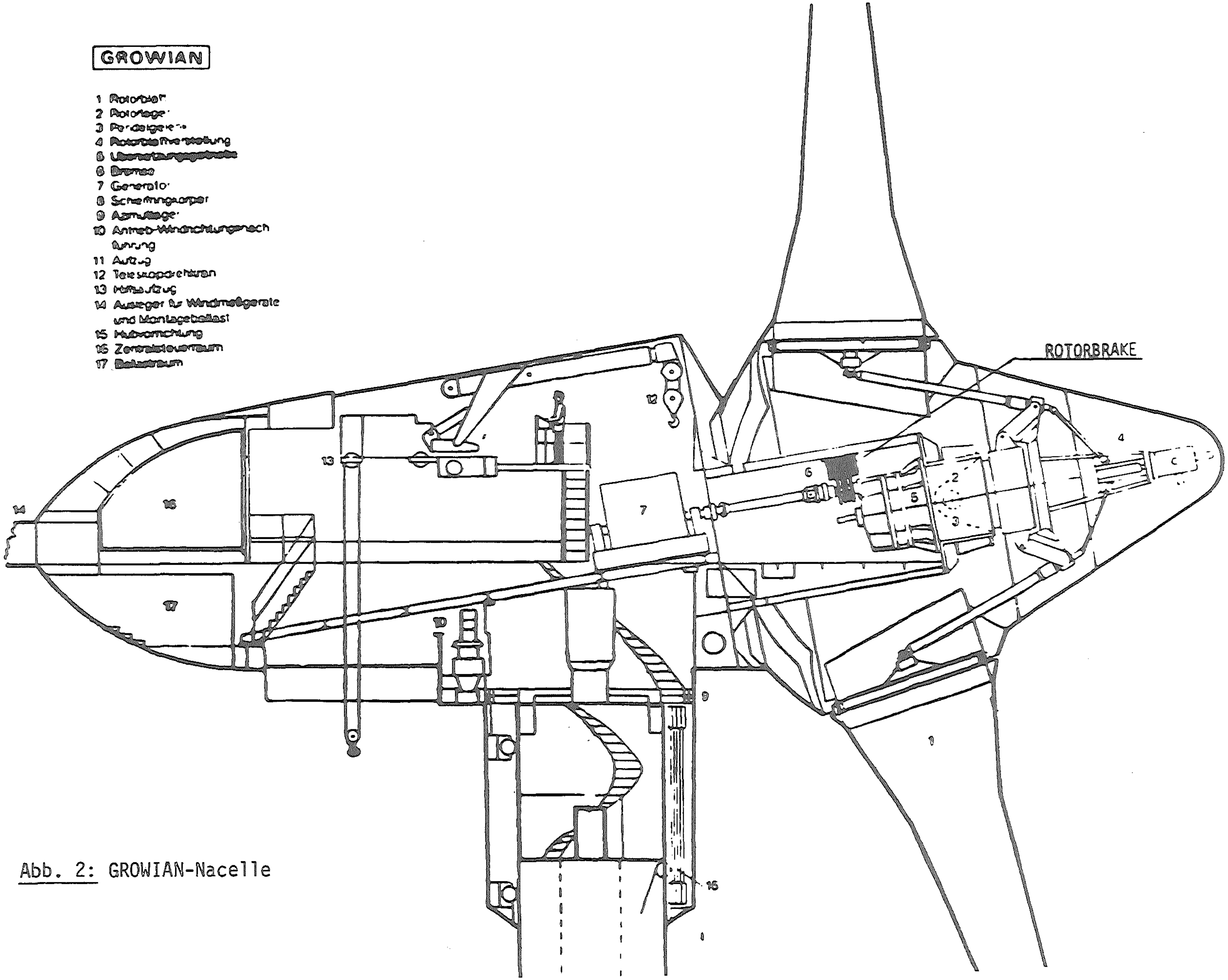


Abb. 2: GROWIAN-Nacelle

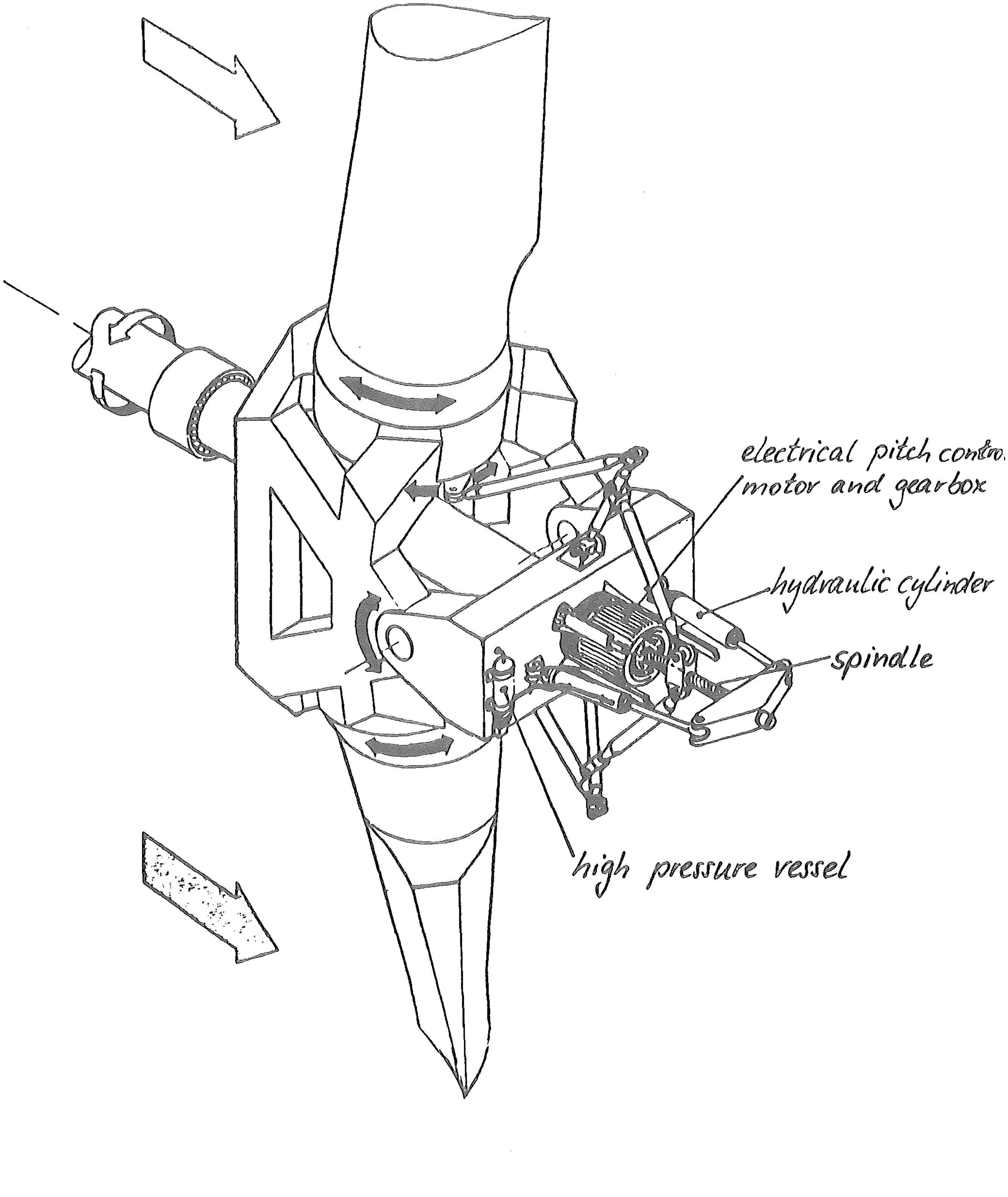


Abb. 3: Teetering Hub with blade pitch control mechanism and hydraulic emergency blade feathering system

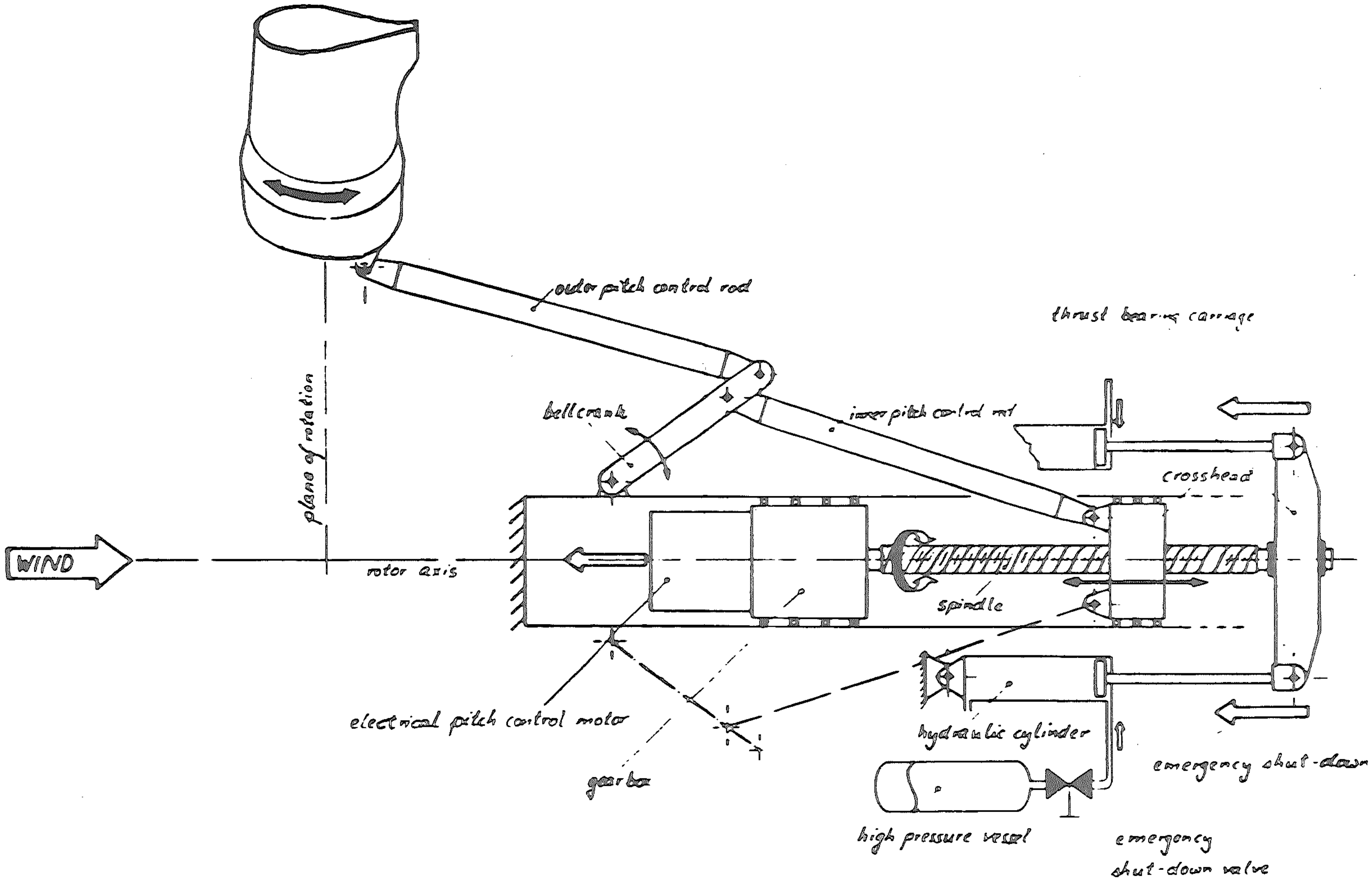


Abb. 4: Functional Diagram of Bladepitch Control System and Hydraulic Emergency Shut-down Mechanism

IV. CONCLUDING REMARKS

The two most important aspects with respect to the evaluation of safety in the operation of the GROWIAN large wind energy plant have been discussed. It goes without saying that further considerations and measures must be taken into account to give a truly comprehensive safety philosophy.

In the continuing development of GROWIAN, therefore, the next necessary step to be taken will have to be a complete "Failure Mode and Effect Analysis" from safety and environmental aspects.

ENVIRONMENTAL CONSIDERATIONS FOR LARGE WIND TURBINE SYSTEMS:

TELEVISION INTERFERENCE

JOSEPH M. SAVINO

TELEVISION INTERFERENCE

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3. D. L. SENGUPTA & T. B. A. SENIOR, "ELECTROMAGNETIC INTERFERENCE TO TELEVISION RECEPTION CAUSED BY HORIZONTAL AXIS WINDMILLS," PROCEEDINGS OF THE IEEE VOL. 67, No. 8, AUGUST 1979, PP. 1133-1142.

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TELEVISION INTERFERENCE (TVI)

BACKGROUND

- LOW FLYING AIRCRAFT IS KNOWN TO CAUSE TVI NEAR AIRPORTS
- IT WAS RECOGNIZED THAT TVI COULD HAVE AN IMPORTANT EFFECT ON THE DEPLOYMENT & PUBLIC ACCEPTANCE OF LARGE WTS

OBJECTIVES

- DETERMINE IF WTS CAN PRODUCE TVI AND OTHER ELECTROMAGNETIC INTERFERENCE
- DETERMINE THE LEVELS OF INTERFERENCE
- ASSESS THE IMPACT OF THESE LEVELS OF WTS SITING
- TO UNDERSTAND, REDUCE, OR ELIMINATE TVI

APPROACH

- CONDUCT A PROGRAM OF INVESTIGATION TO MEET THE OBJECTIVES
  - ON-SITE MEASUREMENTS & TEST WITH MOD-0, MOD-0A & MOD-1
  - LABORATORY TESTS & SIMULATION EXPERIMENTS
  - ANALYTICAL STUDIES

TELEVISION INTERFERENCE (TVI)

MOD-O SITE MEASUREMENTS (REFERENCE 3)

EQUIPMENT

- TWO TV RECEIVERS WITH SUPERIOR INTERFERENCE REJECTION
- SPECTRUM ANALYZER CONNECTED TO PAPER TAPE RECORDER
- VIDEO RECORDER TO RECORD THE DISTORTED VISUAL PORTION

TEST PROCEDURE

- TV RECEIVERS WERE LOCATED
    - BETWEEN THE MOD-O AND TRANSMITTING STATIONS (BACKSCATTER ZONE)
    - WITH MOD-O BETWEEN RECEIVER & TRANSMITTER (FORWARD SCATTER ZONE)
- TRANSMITTERS WERE 67 & 80 KM FROM MOD-O
- UHF & VHF SIGNALS WERE MONITORED
- RECEIVING ANTENNA HEIGHT = 10M

TELEVISION INTERFERENCE (TVI)

SIGNIFICANT RESULTS

- IN BACK SCATTERING ZONE
  - DELAYED MULTI-PATH SIGNAL LEADS TO GHOST IMAGES THAT FLUCTUATE (JITTER) AT 2X ROTOR RPM AND CAN BE VISUALLY OBJECTIONABLE
  - VIDEO DISTORTION IS INDEPENDENT ON TRANSMITTED SIGNAL LEVEL WHEN SIGNAL IS WELL ABOVE THE RECEIVER NOISE LEVEL
  - TVI OBSERVED ONLY WHEN BLADE IS POSITIONED TO DIRECT A SPECULARLY (MIRROR-LIKE) REFLECTED SIGNAL TO THE RECEIVER

    IMPORTANT PARAMETERS ARE:

    -- BLADE AZIMUTH AND PITCH ANGLE

    -- WTS YAW ORIENTATION

    -- DISTANCE OF RECEIVER FROM WTS AND RELATIVE POSITIONS OF TRANSMITTER, WTS AND RECEIVER

SIGNIFICANT RESULTS (CONTINUED)

- FORWARD SCATTERING ZONE
  - TVI APPEARS AS AN INTENSITY MODULATION ON THE TV PICTURE
  - BECAUSE SCATTERED SIGNAL HAS LITTLE DELAY, A GREATER SIGNAL AMPLITUDE IS NEEDED TO PRODUCE TVI COMPARABLE TO TVI IN BACKWARD SCATTERING ZONE
- GENERAL
  - EACH BLADE CONTRIBUTES TO TVI, MAXIMUM WHEN HORIZONTAL
  - TVI INCREASES WITH INCREASING TRANSMITTER FREQUENCY & DECREASE WITH DISTANCE FROM WTS
  - NO TV AUDIO DISTORTION WAS FOUND IN ANY TEST
  - NO INTERFERENCE WITH FM RADIO RECEPTION WAS EXPERIENCED

CONCLUSIONS

- LARGE ROTATING METAL WIND TURBINE BLADES CAUSE TVI
- TVI IS MORE SEVERE IN BACK SCATTER ZONES AROUND THE WIND TURBINE THAN IN FORWARD SCATTER ZONES
- UNACCEPTABLE TVI CAN OCCUR UP TO 3KW DEPENDING ON WIND DIRECTION, RELATIVE LOCATIONS BETWEEN THE WTS, RECEIVER & TRANSMITTER
- SEVERITY OF TVI INCREASES WITH BLADE SIZE & WITH THE INCREASED AMOUNTS OF METAL IN THE BLADES
- TVI IS LESS FOR BLADES MADE OF FIBERGLASS

TELEVISION INTERFERENCE (TVI)

LABORATORY TESTS & ANALYTIC RESULTS

OBJECTIVES

- TO DETERMINE THE MODULATION LEVEL AT WHICH TVI IS FIRST PERCEIVED ON A TV SCREEN
- TO DETERMINE THE MOST SEVERE TVI THAT IS STILL ACCEPTABLE FOR MOST VIEWING PURPOSES

EXPERIMENTAL METHOD

- TRANSMITTED TV SIGNAL INTO TWO BRANCHES
- BRANCH NO. 1 FED DIRECTLY TO TV RECEIVER SIMULATING PRIMARY SIGNAL
- BRANCH NO. 2 SIGNAL PROCESSED TO SIMULATE SIGNAL REFLECTED OF MOVING BLADES
- THE TWO BRANCH SIGNALS ARE RECOMBINED AND THEN FED INTO TV RECEIVER AND THE SPECTRUM ANALYZER
- VIEWERS WERE USED TO OBSERVE AND REACT TO THE CONTROLLED TVI

CATEGORIES OF VIDEO DETERMINED

1. NO VIDEO DISTORTION
2. VIDEO DISTORTION ACCEPTABLE FOR SHORT VIEWING PERIODS
3. DISTORTION JUDGED UNACCEPTABLE
4. PICTURE DISRUPTIVE DISTORTION

RESULTS

- UNACCEPTABLE TVI OCCURS WHEN THE BACK SCATTERED SIGNAL LEVEL IS 15% OR MORE OF THE DIRECT SIGNAL; THIS IS A CONSERVATIVE VALUE
- CALCULATIONS ESTIMATE THE ZONE OF UNACCEPTABLE TVI TO EXTEND UP TO 3 KM

TELEVISION INTERFERENCE (TVI)

MOD-1 EXPERIENCES AT BOONE, NORTH CAROLINA

- THE PROBLEM
  - APPROXIMATELY 33 HOUSEHOLDS AROUND THE SITE UP TO 2 KM COMPLAINED
  - BOONE IS A FAR FRINGE RECEPTION AREA
  - TV RECEPTION IS AGGRAVATED BY THE SURROUNDING MOUNTAINS
  - MOST HOMES HAVE CABLE TV
  - MOD-1 IS ELEVATED 300 METERS ABOVE MOST TV ANTENNAS
    - MOD-1 PROBABLY RECEIVES A STRONGER SIGNAL THAN MOST HOME TV ANTENNAS
    - SCATTERED TV SIGNALS ARE OFTEN STRONGER THAN THE DIRECT SIGNAL, THEREBY CAUSING SERIOUS TVI
- APPROACH TO REDUCING OR ELIMINATING THE TVI
  - IDENTIFY AREAS WITH OBJECTIONABLE TVI
    - FIELD TESTS TO MEASURE TVI (BEFORE & AFTER INSTALLING BETTER ANTENNAS)
    - ANALYTICAL STUDIES TO DETERMINE TVI CRITERIA
  - EVALUATE & SCREEN VARIOUS ANTENNA IN LAB TESTS PRIOR TO FIELD TESTS
  - DETERMINE & IMPLEMENT SOLUTIONS TO HOMES WITH TVI PROBLEM
- RESULTS
  - NONE TO REPORT -- STUDIES WERE RECENTLY INITIATED

TELEVISION INTERFERENCE (TVI)

MOD-OA EXPERIENCE AT BLOCK ISLAND, RHODE ISLAND (REFERENCE 4)

BACKGROUND

- BLOCK ISLAND IS EITHER IN A TV FRINGE AREA OR A DEEPSHADOW AREA
- TYPICAL HOME ANTENNA IS 10 METERS HIGH
- MOD-OA BLADES ARE MUCH HIGHER & RECEIVE A STRONGER SIGNAL

TVI TESTS

- TEST CONDUCTED IN OCTOBER 1979
- OBJECTIVE OF TESTS: TO DETERMINE THE IMPACT OF THE MOD-OA ON TV RECEPTION ON THE ISLAND
- APPROACH: MEASURED TV SIGNALS AT 4 SITES IN THE FORWARD SCATTERING & BACK SCATTERING REGIONS USING SIMILAR TEST PROCEDURE OF THE MOD-0 TESTS
- TEST PARAMETERS
  - -- VARIOUS TV TRANSMITTER FREQUENCIES, DIRECTION & DISTANCE
  - -- MOD-OA OPERATING MODES: ROTATING, NONROTATING, YAW DIRECTION
  - -- SITE LOCATION: DISTANCE & DIRECTION FROM MOD-OA
  - -- ANTENNA CHARACTERISTICS

PRELIMINARY RESULTS

- TV'S WITH POOR ANTENNAS OR INCORRECTLY ORIENTED GOOD ANTENNAS TVI CAN EXTEND TO 1 KM OR MORE FOR SOME CHANNELS
- AT DISTANCES LESS THAN 0.2 KM, IT IS DIFFICULT TO AVOID TVI
- BETWEEN 0.2 & 0.5 KM, WITH A GOOD ANTENNA PROPERLY ORIENTED TVI CAN BE USUALLY AVOIDED
- BEYOND 1 KM, TVI CAN BE AVOIDED WITH A MODERATE QUALITY ANTENNA

App. : Presentation
J.M. Savino : Telev. Int.

Electromagnetic Interference to Television Reception Caused by Horizontal Axis Windmills

DIPAK L. SENGUPTA, SENIOR MEMBER, IEEE, AND THOMAS B. A. SENIOR, FELLOW, IEEE

Abstract—Electromagnetic interference to television (TV) reception produced by horizontal axis wind turbine generators or windmills has been identified and quantified by comprehensive theoretical and experimental studies. It is found that the rotating blades of a windmill can produce pulse amplitude modulation (PAM) of the total signal received, and that for an antenna so located as to pick up the specular or forward scattering off the blades, this extraneous modulation can distort the video portion of a TV signal reproduction in the vicinity of the windmill. The distortion is worst at the higher frequencies, and therefore, poses more of a problem at UHF than VHF. Based on laboratory studies as well as on-site measurements, a modulation level has been established at which the video interference is judged "acceptable," and this threshold of interference is substantially independent of the ambient signal strength. A theory has been developed to compute the interference region about a windmill for any given TV transmitter, and the results are in good agreement with those obtained from on-site measurements with an operational windmill.

I. INTRODUCTION

IT IS POSSIBLE that in years to come large wind turbine generators (WTG) or windmills will be used to generate power not only for rural communities but as inputs to the National Grid, thereby bringing about a revival of one of mankind's earliest methods of harnessing nature [1], [2]. In 1973, a wind energy program was initiated jointly by the National Science Foundation (NSF) and the NASA Lewis Research Center, and in 1975, the responsibility for planning and executing a sustained wind energy program was transferred to the newly formed Energy Research and Development Administration (ERDA), and hence to the U.S. Department of Energy (DOE). As part of the program, a 100-kW WTG was designed and fabricated and is now in operation at the NASA Lewis Plum Brook facility near Sandusky, OH. The rotor of the machine consists of two blades of aerofoil shape with a total diameter of 37.5 m and a fixed coning angle of 7°. The rotor is mounted atop a tower 30 m in height (Fig. 1) and is intended to produce 133 kW of power (100 kW at the actual generator) when rotating at 40 r/min in an 18-mi/h wind [3], [4].

With the knowledge gained from this prototype machine, other and larger generators are being developed and put into operation (e.g., at Clayton, NM, in 1978) and the national goal of energy sufficiency by the 1980's could well see the rapid deployment of this nonpolluting and not visually unattractive system of electric power generators throughout the U.S. [2]. Even as presently conceived, these windmills could have two- or three-blade rotors up to 60 m in diameter [5]. The blades themselves may be twisted and tapered from root to tip, consisting of a metallic skin on a framework of girders or made of composite materials, and with their aerodynamic shape, they would be rather similar to the wings of an aircraft. Because of the observed fact that a low-flying aircraft can interfere with TV reception by producing a momentary jitter or flipping of the picture, it seemed possible that the windmill blades could act in the same manner. Indeed, the problem could be more severe. Whereas aircraft interference is a transitory phenomenon, a windmill would be fixed in its location and affect the performance of TV or other systems in that region of space where the signal scattered off the moving blades is received.

The existence of such interference could have a bearing on the deployment and public acceptance of large horizontal axis windmills as a means of power generation, and a study was

Manuscript received October 16, 1978. This work was supported by the Wind Systems Branch, Division of Solar Technology, Department of Energy, under Contract EY-76-S-02-2846.
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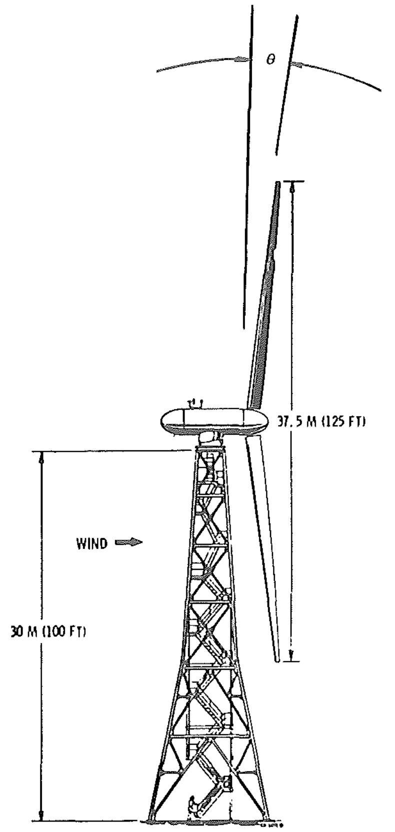

Fig. 1. 100-kW NASA/ERDA experimental WTG at Plum Brook.

therefore undertaken to i) determine if windmills could interfere with TV reception, ii) quantify the levels of interference that were found, and iii) assess the impact of these levels on the siting of windmills. To meet these objectives, a rather comprehensive program was performed involving laboratory measurements and simulation, on-site measurements using the existing NASA/ERDA windmill at Plum Brook, and rigorous analyses and computations. The program also included an investigation of the impact of windmill-produced interference on the performance of broadcast FM receivers, aircraft navigation, and microwave link systems (see [6]-[8] for details), but this paper addresses only the interference to TV reception.

II. General Considerations

For a better appreciation of the studies that were performed and to analyze the various results obtained, it is appropriate to start with a general discussion of windmill-produced interference and the problem of quantifying it theoretically. In a neighborhood of the windmill, the total signal at a TV receiver will consist of the desired direct or primary signal plus a secondary one due to scattering by the windmill. If sufficiently strong, the latter signal may produce unacceptable interference, and its effects on reception can be examined knowing the detection characteristics of the TV receiver.

A. Signal Analysis of TV Reception

The principles of operation of a TV receiver receiving only the direct signal from the transmitter are well known. Nearby stationary objects—like buildings, water towers, bridges, or the stationary blades of a windmill—may produce reflected signals which reach the receiver delayed in time, and such multipath sources can cause multiple images or "ghosts" on a TV picture even when the receiving antenna is matched. Nevertheless, the use of a matched directional suitably oriented antenna will usually correct the problem unless the receiver is located in a region of strong multipath, and we shall therefore ignore the effect of a stationary windmill on TV reception.

In the absence of multipath sources, the composite signal at the input of a receiver may be represented [9] as

$$y(t) = [1 + f_v(t)] \cos(\omega t + \phi_1) + B \cos[(\omega + \Delta\omega)t + \phi_A(t) + \phi_2] \quad (1)$$

where $f_v(t)$ is the video information transmitted in the form of amplitude modulation (AM) of a carrier of radian frequency ω, $d\phi_A(t)/dt = f_A(t)$ is the audio information transmitted as phase (frequency) modulation (PM) of an audio carrier of radian frequency $\omega + \Delta\omega$ ($\Delta\omega$ is called the audio subcarrier, and normally $\Delta\omega/2\pi = 4.5$ MHz), B is the amplitude of the audio carrier level relative to that of the video carrier (usually $B \ll 1$), and ϕ_1, ϕ_2 are the arbitrary constant phases of the video and video carriers, respectively.

The first detector of a TV receiver envelope detects the signal (1). To see the process more clearly, equation (1) is written approximately as

$$y(t) \simeq [1 + f_v(t) + B \cos\{\Delta\omega t + \phi_A(t) + \phi_2 - \phi_1\}] \cos\{\omega t + \phi_1 + \alpha(t)\} \quad (2)$$

with

$$\alpha(t) \simeq \frac{B}{1 + f_v(t)} \sin\{\Delta\omega t + \phi_A(t) + \phi_2 - \phi_1\} \quad (3)$$

from which it is evident that envelope detection yields the undistorted video information $f_v(t)$ and a frequency modulated audio subcarrier signal which, on second detection, gives the desired audio information $f_A(t)$. Low-pass and bandpass filters at the output of the envelope detector separate the video and audio signals and direct them to the appropriate channels of the TV receiver for further processing.

In the stationary multipath situation the detection process can be analyzed in a similar manner to the above, but if the secondary signal is produced by reflection off the rotating blades of a windmill, the crucial distinction is that the equivalent source is now time-varying, leading to extraneous AM and/or PM of the net input to the receiver. Let the video and audio carriers be amplitude and phase modulated by $f_{m_1}(t)$, $\delta_1(t)$ and $f_{m_2}(t)$, $\delta_2(t)$, respectively. Under the approximation $|f_{m_1}(t)|, |f_{m_2}(t)| \leqslant 1$, the composite signal entering the receiver is [6]

$$\begin{aligned} y(t) \simeq [&\{1 + f_v(t)\}\{1 + f_{m_1}(t)\} \\ &+ B\{1 + f_{m_2}(t)\} \cos\{\Delta\omega t + \phi_A(t) \\ &+ \delta_1(t) - \delta_2(t) + \phi_2 - \phi_1\}] \\ &\cdot \cos\{\omega t + \delta_1(t) + \alpha_1(t) + \phi_1\} \end{aligned} \quad (4)$$

where

$$\alpha_1(t) \simeq \frac{B[1 + f_{m_2}(t)]}{[1 + f_v(t)][1 + f_{m_1}(t)]} \sin\{\Delta\omega t + \phi_A(t) + \delta_2(t) - \delta_1(t) + \phi_2 - \phi_1\} \quad (5)$$

and the other quantities are as before. When the signal (4) is envelope-detected, examination of the resulting expressions shows that the video output may be distorted by extraneous AM but not by PM, whereas the audio output is affected by PM only if $\delta_1(t) \neq \delta_2(t)$ and not at all by AM unless this is sufficiently strong to change the efficiency of the second detection in the audio channel. These results have been confirmed [6] by laboratory experiments.

It is therefore concluded that any TV interference that a windmill may provide is most likely to be video distortion attributable to AM of the net input to the receiver. Obviously, the level of interference depends on the nature and magnitude of the modulation which a windmill actually produces, and we will now relate these to the field quantities involved.

B. Fields Received in the Presence of a Windmill

The total electric field at a receiving point R can be written as

$$E(R, t) = E^T(R) + E^B(R, t) \tag{6}$$

where $E^T(R)$ is the direct field of the transmitter T at the receiver R, and $E^B(R, t)$ is the secondary field which reaches R after reflection at a rotating blade B of the windmill. For simplicity the fields will be treated as scalar with an assumed RF time dependence exp $(j\omega t)$ which has been omitted from (6). All of the quantities in (6) are complex, and the time dependence of the secondary field and, hence, total field, is due to the blade rotation. We can separate out the time dependence by writing

$$E^B(R, t) = |E^B(R)|\, f_m(t) \exp\, [i\delta(t)] \tag{7}$$

where $|E^B(R)|$ is the maximum value of the secondary field amplitude during any one rotation of the blade, $f_m(t)$ is a real function of time having maximum value unity, and $\delta(t)$ is the time varying RF phase of the secondary field. If we also express the direct field as

$$E^T(R) = |E^T(R)| \exp\, (i\delta_0)$$

the total field becomes

$$E(R, t) = E^T(R)\ \{1 + mf_m(t) \exp\, [i\tilde{\delta}(t)]\} \tag{8}$$

in which $\tilde{\delta}(t) = \delta(t) - \delta_0$ is the RF phase difference between the secondary and direct fields and

$$m = \left| \frac{E^B(R)}{E^T(R)} \right|. \tag{9}$$

Assuming $m << 1$, the amplitude of the total received signal is then

$$|E(R, t)| = |E^T(R)|\ \{1 + mf_m(t) \cos \tilde{\delta}(t)\} \tag{10}$$

showing the AM resulting from the blade rotation. The modulation index and function are m and $f_m(t)$, respectively, with $|f_m(t)| \leqslant 1$. In the static case $f_m(t) = 1$.

To interpret (10) in terms of observable quantities, we note that as a function of time $\cos \tilde{\delta}(t)$ is rapidly varying compared with $f_m(t)$, and attains its extreme values ±1 many times during a single variation of $f_m(t)$. The envelope of (10) is therefore

$$|E(R, t)|_{\text{envelope}} = |E^T(R)|\ \{1 \pm mf_m(t)\} \tag{11}$$

and represents the total field that is actually observed. The maximum and minimum departures from the ambient level in dB are

$$\Delta_{1,2} = 20 \log_{10} (1 \pm m)$$

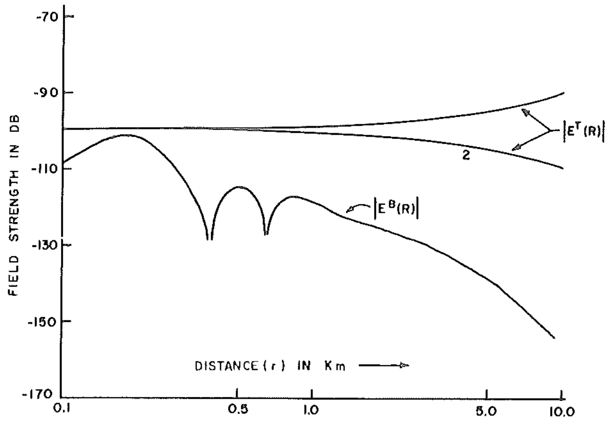

Fig. 2. Calculated field strengths ($|E^T(R)|$, $|E^B(R)|$) as functions of distance (r) from the windmill: f = 650 MHz, transmitter-windmill distance = 80 km, transmitter height = 300 m, receiver height = 10 m, windmill height = 30 m, relative permittivity of earth ϵ = 15, conductivity of earth σ = 0.01℧/M.

giving rise to the (dB) modulation

$$\Delta = \Delta_1 - \Delta_2 = 20 \log_{10} \frac{1 + m}{1 - m}. \tag{12}$$

To calculate m in any given situation, an available computer program [10] was modified [6] to compute $|E^T(R)|$ and $|E^B(R)|$ from the known analytical expressions [11], [12] for an electromagnetic field in the presence of a smooth, homogeneous, spherical earth of arbitrary permeability, permittivity, and conductivity. The program is quite general and computes the field of a horizontally or vertically polarized isotropic antenna radiating 1-kW effective power for specified transmitter and receiver heights and transmitter-receiver separation. In the case of $E^B(R)$, the direct field at the blade is first obtained, and the physical optics approximation is then used to find the amplitude of the field scattered by the blade in the specular direction. The equivalent (flat plate) scattering area determined in this manner is in good agreement with values measured using actual blades as well as small-scale models. From this, the effective strength of the blade regarded as a secondary source of radiation is deduced, and the computer program is invoked again to give the secondary field at the receiver.

As an illustration of the results obtained, Fig. 2 shows the direct and secondary field strengths computed for TV channel 43 (f = 650 MHz) as functions of the distance r of the receiver from the windmill at Plum Brook. The windmill is 80 km from the transmitter and each blade has an equivalent scattering area of 12 m^2. The transmitter, receiver, and windmill are assumed to lie on the same great circle, and curves 1 and 2 are the direct field at a receiver on the near and far sides, respectively, of the windmill as viewed from the transmitter. Because of the large distance of the transmitter from the receiver, the direct field varies rather uniformly with r and is, of course, larger in the first case, whereas the secondary field has a lobe structure out to about 1 km from the windmill. At distances beyond this, the strength of the secondary field relative to the direct field falls off more rapidly on the near side of the windmill, implying that any interference extends out to a smaller distance in this direction. The modulation index m at a given distance is obtained by computing the ratio $|E^T(R)/E^T R|$ from Fig. 2, and will generally decrease with r. As we shall see later, the interference at any point depends crucially on m and, hence, r.

C. Windmill Modulation Function

The modulation function $f_m(t)$ represents the time dependence of the scattered field envelope introduced by the blade rotation, and leads to a time variation in the amplitude of the total received field. The blade rotation frequency may vary, but is typically about 30 r/min (0.5 Hz). If the blade were to produce a continuous (sinusoidal) AM at the rotation frequency, the automatic gain control (AGC) circuit of the TV receiver could almost certainly compensate for it, in which case there would be no video distortion; but if the modulation function were discontinuous (i.e., some sort of repetitive pulse waveform), the higher frequencies which it contains could affect the video reception. It is therefore of interest to examine the type of modulation produced by a windmill.

Since the modulation function is due to blade scattering, it necessarily depends upon the geometry and material of the blade, the blade rotation frequency, the frequency and polarization of the illumination, and the directions of the transmitter and receiver relative to the blade. An exact determination would therefore require the solution of a rather complicated boundary value problem, and though, in principle, it would be feasible to obtain a numerical solution for a sequence of incremented positions of the blade, it is doubtful whether this type of solution would bring out the features that are common to any rotating structure. We shall therefore seek an approximate result sufficient to reveal the gross features of the modulation.

Consider a rectangular metal plate of dimensions L_1 and L_2 lying in the xz plane of a Cartesian coordinate system as shown in Fig. 3. The origin of coordinates is at the center of the plate and is also the origin of a spherical polar coordinate system (r, θ, ϕ). The plate is illuminated by a plane electromagnetic wave incident from the direction θ_0, ϕ_0 with its electric vector in the xy plane, i.e., horizontal, and the scattered field is received in the direction θ, ϕ. For a plate rotating in the xz plane at an angular frequency Ω, the modulation waveform of the horizontal component of the scattered electric field is [6], [13]

$$f_m(t) = \operatorname{sinc}\left\{\frac{L_1}{\lambda}(p \sin \Omega t + q \cos \Omega t)\right\} \cdot \operatorname{sinc}\left\{\frac{L_2}{\lambda}(p \cos \Omega t - q \sin \Omega t)\right\} \quad (13)$$

where

$$p = \sin \theta_0 \cos \phi_0 + \sin \theta \cos \phi$$

$$q = \cos \theta_0 + \cos \theta$$

$$\operatorname{sinc} x = \frac{\sin \pi x}{\pi x}$$

and λ is the wavelength of the incident illumination.

For a high aspect ratio plate, $L_1 >> L_2$, and the time dependence of $f_m(t)$ is primarily determined by the first factor in (13). The equation then shows that in the directions of specular and forward scattering ($\phi = \pi - \phi_0$ and $\pi + \phi_0$, respectively) where the scattering is a maximum, the modulation is independent of time. In directions near to these, however, the modulation function is a sinusoid with frequency twice the rotation frequency, and in directions which are well away, the waveform consists of sinc-like pulses of width proportional to L_1^{-1} repeating at twice the rotation frequency. Measured data [6], [13] support these conclusions, and Figs. 4(a)–(c) show the modulation observed with a rotating plate for three different combinations of incident an receiving directions.

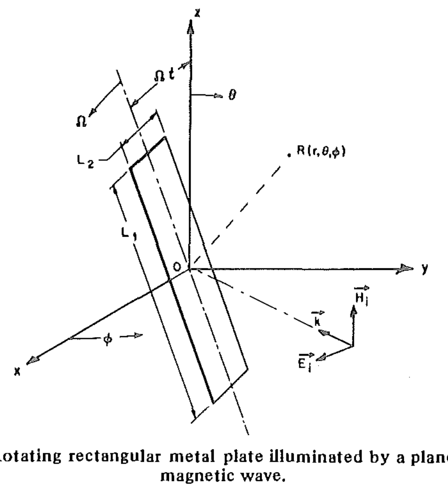

Fig. 3. Rotating rectangular metal plate illuminated by a plane electromagnetic wave.

The fact that there is no time-varying modulation in the directions of maximum scattering is a consequence of choosing a planar plate rotating in its own plane, and is not true in a more realistic situation of a blade which is nonplanar and/or twisted out of its plane of rotation. Nevertheless, our simple model is capable of providing meaningful information for an actual blade if we confine attention to directions somewhat away from those of maximum scattering. For a remote transmitter we can choose $\theta_0 = \pi/2$. The specular direction is then $\theta = \pi/2$, $\phi = \pi - \phi_0$, but because the windmill is usually much higher than the receiving antenna, it is possible that the closest we can come to this direction is $\theta = \pi/2 + \alpha$, $\phi = \pi - \phi_0$, where α is some small nonzero angle. Under these conditions, equation (13) implies

$$f_m(t) \simeq \operatorname{sinc}\left(\frac{L_1}{\lambda} \sin \alpha \cos \Omega t\right) \operatorname{sinc}\left(\frac{L_2}{\lambda} \sin \alpha \sin \Omega t\right). \quad (14)$$

For $L_1 >> L_2$, the modulation pulse is primarily determined by the first factor, and if its width $2t_1$ in time is measured by the separation of the first minima on either side of the maximum,

$$t_1 = \frac{1}{\Omega} \sin^{-1}\left\{\left(\frac{2L_1}{3\lambda} \sin \alpha\right)^{-1}\right\}. \quad (15)$$

This type of pulse modulation is capable of producing video distortion.

III. On-Site Measurements of TV Interference

The interference caused by the NASA/ERDA windmill was observed and studied by conducting a number of on-site measurements of the TV signals available at Plum Brook.

A. Measurement Procedure

The relevant features of the windmill and a systematic procedure for conducting the tests are described in [6], [7] and will not be repeated here. A typical experimental arrangement is shown in Fig. 5, where only those components which

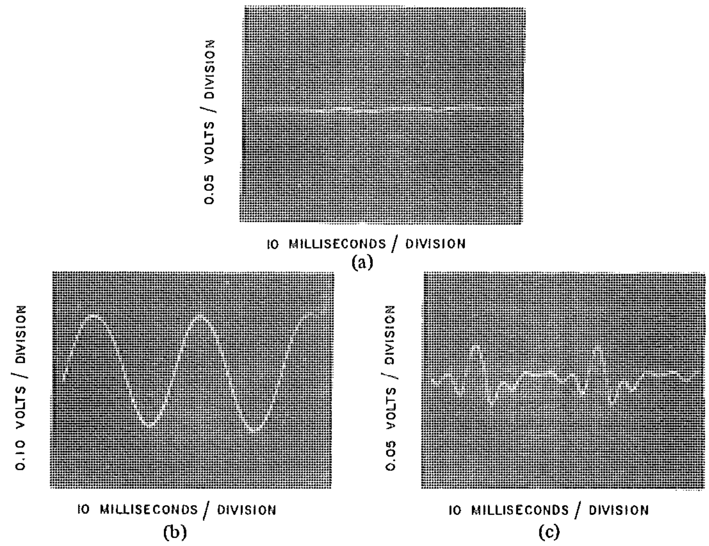

Fig. 4. Experimental modulation waveforms for a rotating rectangular metal plate: $f = 12.18$ GHz ($\lambda = 2.461$ cm), plate rotation frequency = 10 Hz, $L_1 = 5\lambda$, $L_2 = 2\lambda$. (a) $\phi_0 = 135^\circ$, $\phi = 45^\circ$. (b) $\phi_0 = 115^\circ$, $\phi = 55^\circ$. (c) $\phi_0 = 145^\circ$, $\phi = 55^\circ$.

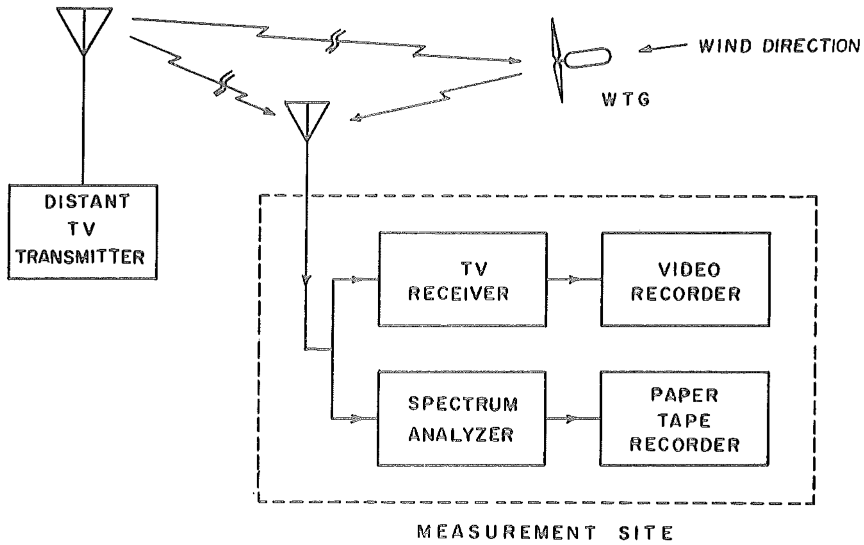

Fig. 5. Schematic block diagram of a typical on-site measurement setup.

are pertinent to the data collection have been included. The TV signals were those of Channels 3, 5, 8, 25, and 43 whose transmitters are located in Cleveland, OH, approximately 80 km away, and Channel 13 with its transmitter in Toledo, OH, 67 km away. Two TV receivers were used: a 1976 Zenith model 17GC45 which has been rated [14] superior for its rejection of interference, and a 1977 Curtis Mathis model B317. With any given TV channel, a portion of the signal is scattered off the windmill blades and this, together with the direct signal, was picked up by the receiving antenna and fed simultaneously to the test receiver and a spectrum analyzer. The receiving antenna was a commercially available directional antenna placed 10 m above the ground.

The received TV program was observed to see if there was any video distortion and, in the initial tests, the signal after detection was fed to a video recorder whenever the picture was worth preserving. On occasion, however, it was found that the windmill interference actually caused the video recorder to lose synchronization, thereby adding distortion to that rightfully attributable to the windmill. We therefore used a TV camera to photograph the picture on the screen of the test receiver, thereby assuring a faithful and reproducible color video recording.

The spectrum analyzer was tuned to the audio carrier frequency of the TV signal. Its vertical output was recorded on paper tape to provide a record of the total received signal level as a function of time, including any modulation produced by scattering from the windmill blades. At both the test site and the WTG control center the WWV time code was recorded to permit subsequent correlation of the interference with the

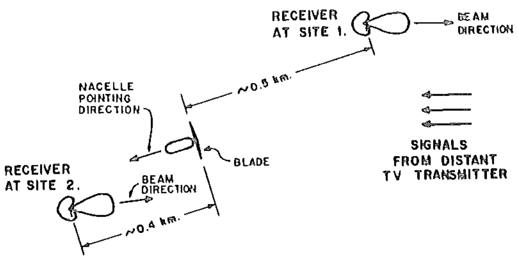

Fig. 6. Geometry of the receiver, transmitter, and windmill during on-site measurement.

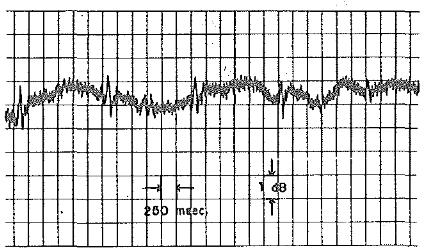

Fig. 7. Received Channel 43 signal showing the modulation pulses due to the backward scattering by the WTG blades. Blade rotation frequency = 20 r/min.

windmill configuration, e.g., pointing direction, blade azimuth position, etc.

B. Total Signal Received

For brevity we shall discuss only the results obtained with TV Channel 43 at receiving sites 1 and 2 (see Fig. 6) located 0.5 and 0.4 km, respectively, from the windmill. At both sites the main beam of the antenna was directed at the transmitter so as to maximize the direct signal received. As a result, at site 1 any specular scattering off the windmill blades was picked up by the backward lobe of the antenna, and at site 2 the almost-forward scattered field was received by the main beam. It is important to note that at the first site, typical of those in the "backward" (scattering) zone, there is a time delay between the arrival of the direct and scattered fields, whereas at the second site, typical of the "forward" (scattering) zone, the delay is negligible.

Fig. 7 shows the total received signal as a function of time at site 1. The pulse-like modulation produced by the blades rotating at 20 r/min is clearly evident. The pulses repeat every 1.5 s, indicating that the blades scatter singly, and a barely visible amount of video distortion was found to occur in synchronism with the pulses. The deviations of the received signal above and below the ambient level are about 0.8 and 1.0 dB, respectively, implying a modulation index $m \simeq 0.11$. Using the theory presented in Section II-B and taking account of the directional properties of the antenna, the predicted deviations are 0.9 and 1.0 dB, implying $m = 0.10$, in excellent agreement with the observations. However, the measured time duration of the pulses is only in fair agreement with the predicted value 172 ms obtained from (15) with $L_1 = 40\lambda$, $\alpha = 5.5°$, and $\Omega = 2\pi/3$ rad/s.

A recording of the output from the spectrum analyzer at site 2 is presented in Fig. 8, and shows the modulation pulses produced by the rotating blades. The modulation index in this case is 0.13, which is slightly higher than for Fig. 6. However, no video distortion was observed and, as we shall see later, this is attributable to the negligible time delay between the direct and scattered signals.

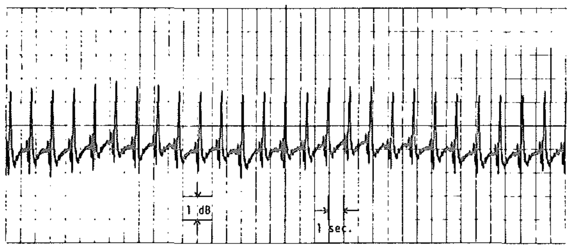

Fig. 8. Received Channel 43 signal showing the modulation pulses due to the forward scattering by the WTG blades. Blade rotation frequency = 20 r/min.

C. Observed Interference

The above are only two examples of the on-site data that were gathered. The entire series of measurements is described in [6], [7], and from the results obtained, the following conclusions can be drawn.

For a receiver in the backward scattering zone of the windmill, the delayed multipath signal leads to a ghost image on the TV screen that, at low and moderate levels of interference, jitters horizontally in synchronism with the blade rotation to produce a form of video distortion that can be quite painful to the eye. In the forward zone, the interference appears as an intensity modulation of the received picture, again in synchronism with the blade rotation, and a somewhat larger modulation index is now required to give the same level of video distortion. In both cases noticeable distortion occurs only when the modulation waveform is pulsed in nature. Each blade contributes individually and the resulting sinc-like pulse usually appears when the blade is close to horizontal. All other things being equal, the modulation index and the resulting video distortion increase with increasing TV channel numbers, i.e., frequency, and with decreasing distance from the windmill. No audio distortion was found in any of the tests.

The following additional conclusions relate to a receiver in the backward scattering zone. The video distortion shows no significant dependence on the ambient level of the signal, provided this is well above the noise level of the receiver, and appears independent of the test receiver used. Interference is observed only when a blade is positioned to direct a specularly reflected signal to the receiver. The azimuth and pitch angles of the blades are therefore key factors affecting the level of interference, and for any given transmitter and receiver locations, interference can occur only if the wind is such as to position the windmill appropriately.

IV. Laboratory Simulation Study

The measurements at Plum Brook verified that a windmill could distort the video portion of a TV signal and showed how the distortion depended upon some of the parameters involved. Because of the environmental conditions near to the windmill and the lack of a full range of receiver sites, the results were necessarily limited in scope, but the information gained from these and other [6] measurements made it possible to simulate the interference, and to examine the distortion under the controlled conditions that a laboratory affords. The key objectives of the study were to establish the modulation level at which the interference is first perceived on a TV screen, and the threshold level corresponding to the most severe interference still judged to be acceptable for most viewing purposes. The latter specified the maximum extent of the interference region about a windmill.

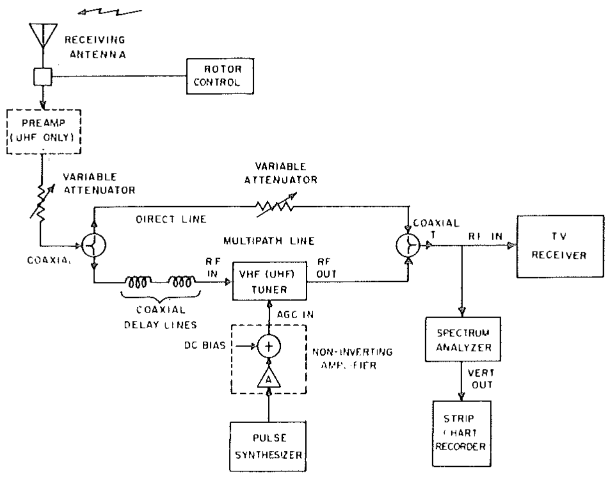

Fig. 9. Block diagram showing the experimental arrangement for simulation and measurement of interference by a WTG.

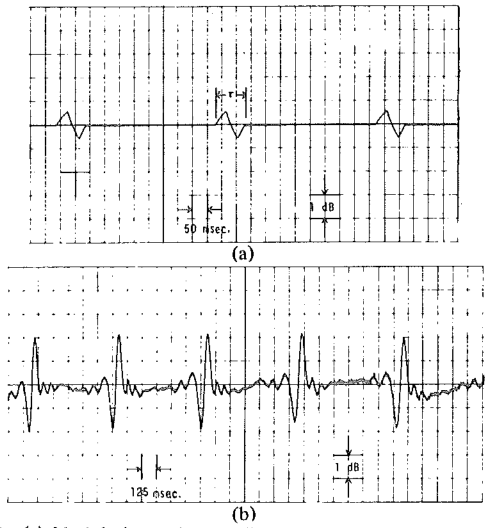

Fig. 10. (a) Modulation pulses applied to the input of the test receiver during the simulation measurement. (b) Modulation pulses at the input of the test receiver observed during the on-site measurement (Channel 43) at Plum Brook. Blade rotation frequency = 40 r/min.

A. Experimental Setup

Fig. 9 shows a block diagram of the equipment. The TV signal was received with a commercial log-periodic antenna mounted on the roof of the laboratory about 120 ft above the ground. With the UHF channels it was found desirable to use a preamplifier, but this was bypassed at VHF where the signals were stronger. The signal was taken through a set of variable attenuators to a coaxial T-junction where it was split into two branches, the direct line representing the primary signal from the transmitter to the receiver, and the multipath line simulating the signal reflected off the moving windmill blades. Simulation was effected by a time delay followed by a repetitive pulse amplitude modulation. The signals were then recombined and fed to the test receiver and a spectrum analyzer. The latter was always tuned to the audio carrier frequency of the particular TV channel, and its vertical output was fed to a strip chart recorder to show the input to the test receiver as a function of time. The strip chart was used to determine the effective modulation level and could be set to a desired value with the attenuators and the dc bias at the AGC terminals of the receiver's tuner.

Fig. 10(a) is typical of the modulation waveforms applied and should be compared with the waveform in Fig. 10(b) measured on Channel 43 at Plum Brook. Since the blades were rotating at 40 r/min, the pulse repetition period in Fig. 10(b) is 0.75 s, but for convenience all our laboratory tests were made with a repetition period of 0.5 s, corresponding to a blade rotation speed of 60 r/min. The change does not affect the nature of the interference phenomena, and in all other respects the study provided a faithful simulation of the interference provided by a windmill such as the one at Plum Brook.

B. Test Procedures

The tests were made with the Zenith receiver used at Plum Brook and a 1967 Airline model GEN 12349A which is typical of older color receivers. The RF signals were the TV Channels 2, 4, 7, 9, and 50 whose transmitters are located near Detroit, MI, approximately 60 km from the laboratory, and Channels 11, 13, and 24 originating in Toledo, OH, about 90 km away. Each channel was modulated with pulses of width $\tau = 50$ 100 or 200 ms having a 500-ms repetition period. The backward zone interference was simulated by introducing a time delay between the direct and multipath signals and suitably attenuating the latter. Two sections of coaxial line provided a constant 625-ns delay at all of the TV frequencies, corresponding roughly to the time delay in one of the Plum Brook measurements. For the forward zone the direct line in Fig. 9 was eliminated, so that only the modulated signal was applied to the receiver and the spectrum analyzer.

For a given TV channel and modulation pulse width, each simulation test had two parts. The first served to establish the critical modulation level as a function of the ambient RF signal at the input to a receiver. This is defined as the smallest modulation Δ_c which produces video distortion detectable to an observer viewing the picture from a distance of 5 ft. Although the criterion is obviously subjective, the same observers were used throughout the study and the results were reproducible when the tests were repeated at a later time. In the second part of the test, the modulation Δ was increased in small steps from zero and the degree of video distortion observed. Four categories of video reception were distinguished: i) no video distortion, corresponding to $\Delta < \Delta_c$; ii) distortion judged acceptable for at least small periods of viewing. This corresponds to $\Delta_c < \Delta < \Delta_0$ the upper limit being the modulation threshold; iii) distortion judged unacceptable and intolerable for prolonged viewing; and iv) disruptive distortion ($\Delta \geqslant \Delta_1$) occasionally resulting in picture breakup due to loss of vertical sync by the test receiver.

C. Results

The simulation tests performed were quite extensive, and we present here only the results obtained for modulation pulses of width $\tau = 100$ ms, which is typical of the windmill at Plum Brook.

With both branches of the signal path (see Fig. 9) in operation, simulating backward zone interference, the critical modulation Δ_c for the two receivers and a variety of signal strengths on each of the available TV channels is shown in Table I(a), (b). Data which are of questionable accuracy are marked with symbols whose meaning is explained in the caption, and due to systematic and occasionally erratic valuations in the signal strength of Channel 13, all of the data in Table I(a) are suspect

TABLE I

(a) The Zenith Receiver

Signal (dB/mW)	TV Channel No. 2	4	7	9	11	13	24	50
-50	4.0	–	0.9	–	–	–	–	–
-55	3.4	1.0	0.8	–	0.8	3.8*	–	0.6
-60	4.6	1.2	1.0	0.8	0.9	4.0*	0.6	0.7
-65	4.9	0.9	1.0	0.8	0.8	3.0*	0.7	0.7
-70	4.8	1.1	1.2	1.1	0.9	2.9*	0.9	2.0#
-75	–	1.0	1.5#	1.6	1.0	3.0*	1.2#	2.0#
-80	–	2.6#	1.6#	2.1#	1.3#	3.0#	–	–
-85	–	2.7#	1.7#	2.0#	1.6#	3.2*#	–	–

(b) The Airline Receiver

Signal Level (dB/mW)	TV Channel No. 2	4	7	11	13	24	50
-50	0.8	–	2.2	–	–	–	–
-55	0.5	1.5	2.1	0.9	2.9	–	1.9
-60	0.4	1.4	1.5	0.8	3.3	1.6	1.8
-65	0.5*	1.3	1.8	0.8	3.1	1.5	1.6
-70	0.4*	1.6	1.2	0.8	2.5	1.9	1.8
-75	0.4*	1.8	1.2	0.8	2.2	1.8	1.8#
-80	0.4*	1.8	1.2	0.6#	2.0#	1.8	2.0#
-85	0.4*#	–	–	0.8#	2.0#	–	–

Critical modulation level Δ_c (in dB) required to produce minimum observable video distortion in the backward zone as a function of the ambient audio carrier signal strength on various TV channels.
#Signal very weak and picture "snowy": data unreliable.
*Ambient signal variations large: data mostly unreliable.

for this channel. For completeness, however, the data are included. The degrees of video distortion observed on the two receivers are listed in Tables II(a), (b) for Channels 7 and 50, selected because of the reliability and consistency of the data they provided. Since the results for the Zenith receiver were the same at all signal strengths, Table II(a) shows only the data for an ambient signal–60 dB/mW, but even with the Airline model, Δ_c and Δ_0 are almost independent of the signal level.

With the direct signal path in Fig. 9 eliminated, simulating forward zone interference, the critical modulation Δ_c is shown in Table III. For the Zenith receiver Δ_c decreases rapidly with decreasing signal strength whereas the Airline model's sensitivity is almost uniform, but with both receivers the values of Δ_c at all signal levels exceed those for the backward interference zone. The modulation threshold Δ_0 behaved in a similar manner.

The results indicate that there is no single value of the modulation threshold applicable to all signal levels in both the back and forward interference zones, but since the backward zone encompasses the majority of space around a windmill and here Δ_0 is almost constant at 2.6 dB, this value was chosen for the entire region about a windmill where unacceptable video distortion may occur. From (12) the corresponding threshold modulation index is $m_0 = 0.15$, and one effect of using this is to overestimate the actual video distortion in the forward zone, particularly for high signal levels.

V. TV Interference Region of a Windmill

The judicious siting of a windmill requires a knowledge of its interference to TV reception in its surrounding area. The results of the previous sections indicate that the AM of the

TABLE II

(a) The Zenith Receiver for an Audio Carrier Signal Strength -60 dB/mW

Channel No.	Δ_c(dB)	Δ_0(dB)	Δ_1(dB)
7	1.1	2.8	3.1
50	0.7	2.6	3.0

(b) Airline Receiver as a Function of the Audio Carrier Signal Strength

Signal Level (dB/mW)	Δ_c(dB)	Δ_0(dB)	Δ_1(dB)
Channel 7			
-55	2.1	2.5	5.4
-60	1.5	2.6	7.5
-65	1.8	2.7	6.1
-70	1.2	3.0	5.5
Channel 50			
-55	1.9	2.8	4.3
-60	1.8	2.6	4.2
-65	1.6	2.6	4.4
-70	1.7	2.7	4.4

Modulation levels required for different degrees of backward zone video distortion on two TV channels observed.

TABLE III

Signal Level (dB/mW)	Zenith Channel 7	Zenith Channel 50	Airline Channel 50
-50	29	–	–
-55	25	–	2.6
-60	20	–	2.9
-65	15	17	3.0
-70	5.5	13	3.2
-75	3.5	10	3.2
-80	3.5	5	2.8#
-85	2	4	2.6#

Critical modulation level Δ_c (in dB) required to produce minimum observable video distortion in the forward zone as a function of the ambient audio carrier signal strength.

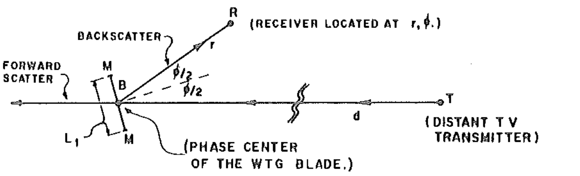

Fig. 11. Geometry of the WTG blade scattering.

total received signal generally decreases with increasing distance from the windmill, and that the video distortion could be unacceptable if the modulation index m is greater than or equal to a threshold value $m_0 = 0.15$. On the assumption that the orientation of the windmill and the pitch and coning angles of the blades are such as to direct the maximum scattered signal to the receiver, the region about the windmill where $m \geqslant m_0$ is defined as the interference region. It should be emphasized, however, that the situation is not "black and white;" and since the interference decreases with increasing distance, the boundary of the region is simply the distance at which the

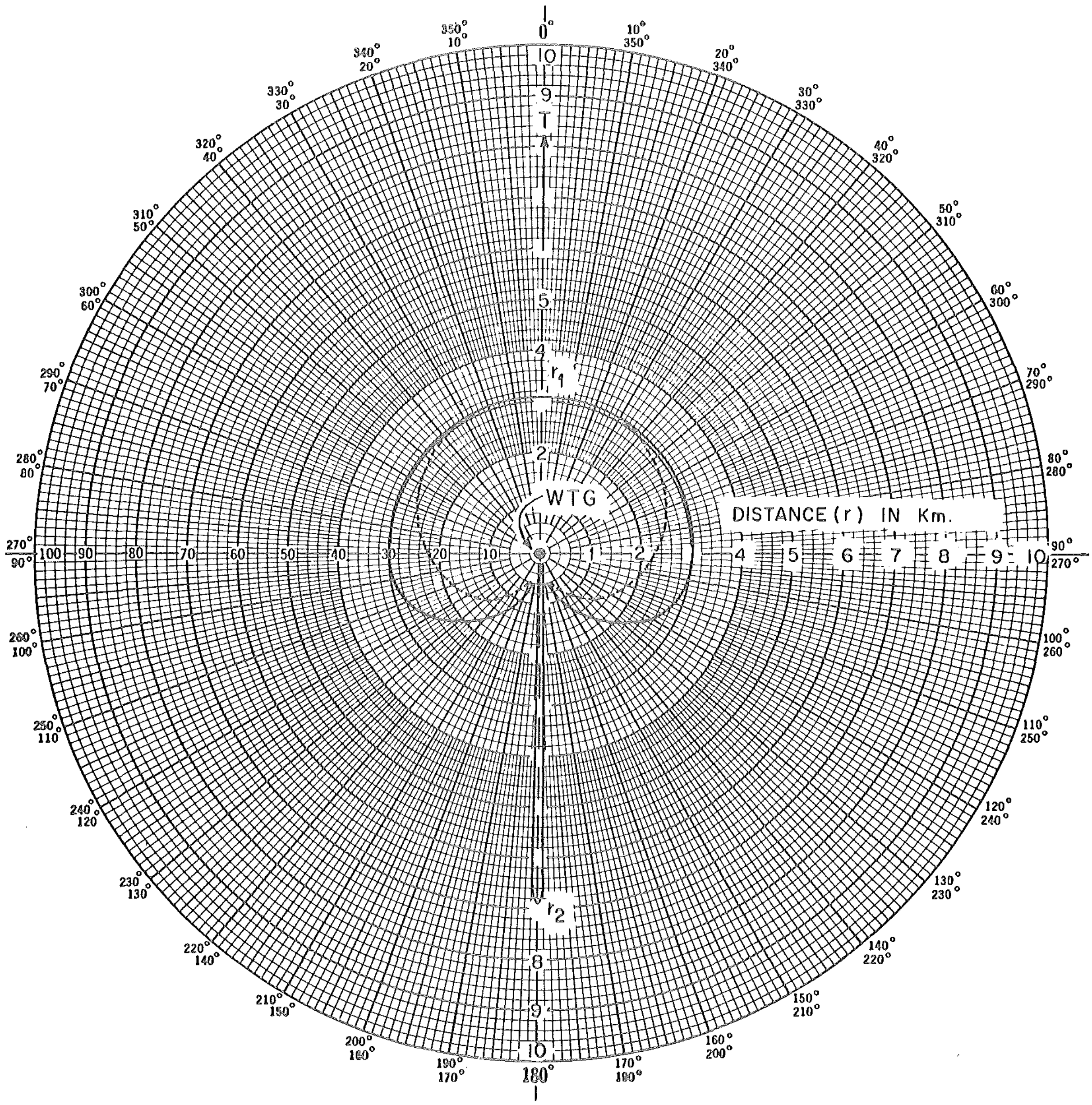

Fig. 12. TV interference region of the NASA/ERDA WTG at Plum Brook for TV Channel 52 (transmitter distance = 120 km), computed using the graphical (——) and approximate (----) methods.

distortion is judged to pass from unacceptable to acceptable for small periods of viewing.

Using computed data for the field strength as a function of distance over a smooth homogeneous spherical earth for specified transmitter and receiver heights, in conjunction with the theoretical relations presented earlier, a graphical method has been developed [8] to determine the interference region in any given situation. It is also possible to determine the approximate shape of the region using elementary considerations, relying on the graphical comparison to specify maximum dimensions, and since this is a much simpler procedure, we shall confine our discussion to it.

Let the scattering center of the windmill and the phase centers of the receiving and (distant) transmitting antennas all lie in the horizontal plane shown in Fig. 11. The windmill blades rotate in a vertical plane through M-M (see Fig. 11) so oriented as to direct the specularly reflected or forward scattered field to the isotropic receiver. The modulation index of the total received field is the ratio of the secondary and direct field amplitudes at R, and since the secondary field is proportional to the direct field $E^T(B)$ at the windmill and the equivalent scattering area A_e of the blade, we can write approximately

$$E^B(R) = E^T(B)\frac{A_e}{\lambda_r}\begin{cases}\cos\phi/2, & \text{for } 0 \leqslant |\phi| \lesssim \pi - \lambda/L \\ \operatorname{sinc}\left(\dfrac{L}{\lambda}\sin\phi\right), & \text{for } \pi - \lambda/L \lesssim |\phi| \leqslant \pi\end{cases} \quad (16)$$

where r is the distance of the receiver from the windmill, and L is the physical length of the blade.

For given $E^T(B)$ and r, $E^T(R)$ achieves its maximum value in the directions $\phi = 0$ and π of backward and forward scattering, respectively, and the distances r_1 and r_2 in these directions at which the modulation index equals its threshold m_0 are

$$r_1 = \frac{A_e}{\lambda m_0}\left|\frac{E^T(B)}{E^T(R_1)}\right|$$

$$r_2 = \frac{A_e}{\lambda m_0}\left|\frac{E^T(B)}{E^T(R_2)}\right| \tag{17}$$

with $R_1 = (r_1, 0)$ and $R_2 = (r_2, \pi)$. These are implicit relations from which r_1 and r_2 can be obtained using the computed field strength curves. In general, $|E^T(R_2)| < |E^T(R_1)|$ implying $r_2 > r_1$. From (16) the backward portion of the interference region is given by

$$r(\phi) = r_1 \cos \phi/2, \qquad 0 \leqslant \phi \lesssim \pi - \lambda/L \tag{18}$$

which is a cardioid centered on the windmill with its maximum towards the transmitter. The forward portion of the region is

$$r(\phi) = r_2 \text{ sinc}\left(\frac{L}{\lambda} \text{ sinc } \phi\right), \qquad \pi - \lambda/L \lesssim \phi \leqslant \pi \tag{19}$$

which is a narrow lobe pointing away from the transmitter. The approximations inherent in this approach are to assume that the propagation of the scattered signal from the windmill takes place as though over a flat earth, and to neglect the ϕ variation of the transmitter–receiver distance in using the field strength curves. As an illustration of the accuracy obtained, Fig. 12 shows the interference region for the NASA/ERDA windmill on Channel 52 computed using the exact [8] and approximate methods. Observe that the region of unacceptable interference extends out several kilometers from the windmill, but it should be emphasized that the calculations were performed on the basis of an omnidirectional receiving antenna and an idealized earth. If the antenna is not omnidirectional, the interference region will differ in all directions except $\phi = 0$, and the effects of local topography could also decrease (or increase) the level of interference at any given location.

VI. Conclusions

The electromagnetic interference to television reception caused by a horizontal axis windmill has been examined theoretically and experimentally. The most important conclusion is that the rotating blades produce PAM of the total received signal, and if the modulation is sufficiently strong, it can distort the video portion of the TV signal. The modulation pulses and the resulting interference have been predicted theoretically, and recorded and characterized experimentally using the operating NASA/ERDA windmill at Plum Brook. It is found that the level of observed interference increases with frequency and is therefore worst at the upper UHF frequencies. It decreases with increasing distance from a windmill, but in the most severe cases it can still produce objectionable video distortion at distances up to a few kilometers. No audio distortion has been observed.

Based on laboratory simulation studies confirmed by field tests, a modulation threshold level has been established below which the video distortion is judged acceptable for short periods of viewing, and this is substantially independent of the ambient field strength and the TV receiver. Using the threshold value and the theory that has been developed, it is then possible to compute the distance from a windmill at which the interference to a TV channel changes from "severe" to "acceptable": in effect, to compute the region of interference about the windmill. The size of this region increases with increasing scattering by the windmill blades and is therefore greater for a larger blade and for metallic rather than composite materials. In our calculations it has been assumed that the receiving antenna is omnidirectional with the windmill positioned to direct the maximum blade-scattered signal to be receiver. In circumstances other than this, the interference will be less, and local topography could also affect the actual interference observed. Depending on the prevailing winds, some (or all) parts of the interference region could suffer interference for only a small fraction of the total viewing time.

Acknowledgment

It is a pleasure to acknowledge the assistance of our colleagues in the performance of this study. We are particularly grateful to J. E. Ferris, who was responsible for the on-site measurements and the measurements of blade scattering; I. J. LaHaie, for contributions to various theoretical and experimental phases of the program; W. F. Parsons, for his help during the measurements; and the personnel of the University of Michigan Television Center, for their advice and counsel with regard to video recording.

Successful completion of the on-site measurements would not have been possible without the help of J. Glassco of the NASA Lewis Research Center who was instrumental in coordinating our on-site measurements, and we also acknowledge the assistance provided by D. Cooksey and H. Phanner of the Plum Brook Facility.

Finally, we are grateful for the support, moral as well as financial, of the DOE Wind Energy Projects Office, and the advice and encouragement of Dr. L. V. Divone and Dr. D. D. Teague were much appreciated.

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ENVIRONMENTAL CONSIDERATIONS FOR LARGE WIND TURBINE SYSTEMS:

SOUND GENERATION

JOSEPH M. SAVINO

SOUND GENERATION

REFERENCES

1. J. R. BALOMBIN, "AN EXPLORATORY SURVEY OF NOISE LEVELS ASSOCIATED WITH A 100 KW WIND TURBINE NASA TM 81486, APRIL 1980.

2. G. C. GREENE AND H. H. HUBBARD, "SOME CALCULATED EFFECTS OF NON-UNIFORM INFLOW ON THE RADIATED NOISE OF A LARGE WIND TURBINE", NASA TM 81813, MAY 1980.

SOUND GENERATION

BACKGROUND

- NO DATA REPORTED ON SOUND GENERATION BY LARGE WTS IN THE PAST
- MOD-0 BLADES PRODUCED SWISHING SOUND AUDIBLE ONLY CLOSE TO THE MACHINE
- QUANTITATIVE DATA WAS NEEDED FOR ENVIRONMENTAL IMPACT ASSESSMENT

MOD-0 SOUND MEASUREMENTS (REFERENCE 1)

- OPERATING PARAMETERS:
  - 40 RPM WITH 30 TO 40 KW OUTPUT
  - 26 AND 33 RPM WITH 60 KW OUTPUT
- MEASUREMENT LOCATIONS:
  - DISTANCES FROM MOD-0 WTS = 30, 60, 120 METERS
  - ANGULAR POSITIONS AROUND MOD-0: 0^{o} (UPWIND)TO 180^{o} (DOWNWIND) IN 20^{o} INCREMENTS
  - EQUIPMENT: MICROPHONES - BRUEL & KJAER MODELS 4133 & 4161 WITH FLAT RESPONSE TO 10 HZ. BELOW 10 HZ CORRECTIONS WERE APPLIED, SOUND WAS RECORDED ON TAPE RECORDERS
- MEASUREMENTS WERE LIMITED TO BELOW 3000 HZ BECAUSE SOUND LEVELS ABOVE 3000 HZ WERE BELOW THE TAPE RECORDED NOISE LEVELS

SOUND GENERATION

MOD-0 SOUND MEASUREMENTS (CONTINUED)

- TEST RESULTS
  - BACKGROUND SOUND LEVELS WERE FROM 45 TO 55 DBA
  - 40 RPM AND 30 TO 40 KW OUTPUT
    - -- AT 30 METERS, SOUND LEVELS WERE 58 TO 64 DBA
    - -- AT 120 METERS, SOUND LEVELS WERE 53 DBA
    - -- BELOW 20 HZ, SOUND LEVELS WERE WELL BELOW THE ANNOYANCE THRESHOLD OF 90 TO 120 DBA
  - 26 AND 33 RPM AND 60 KW OUTPUT
    - -- SOUND <u>PRESSURE</u> LEVELS ARE GENERALLY HIGHER FOR 33 RPM OPERATION THAN AT 26 RPM
    - -- SOUND <u>POWER</u> LEVELS ARE HIGHER AT ALL FREQUENCIES (1 TO 3000 HZ) AT 33 RPM THAN AT 26 RPM
- CONCLUSIONS
  - SOUND PRESSURE LEVELS NEAR THE MOD-0 WTS IN THE FREQUENCY RANGE FROM 1 TO 3000 HZ ARE WELL BELOW THE ANNOYANCE THRESHOLD

SOUND GENERATION

MOD-1 EXPERIENCE (2 MW)

BACKGROUND

- 15 HOUSEHOLD NEAR THE MACHINE HAVE REPORTED AN AUDIBLE "THUMPING" NOISE.
- IN SOME CASES, VIBRATIONS WITHIN THE HOMES HAVE BEEN REPORTED
- ONLY A FEW OF THESE HOUSEHOLDS CONSISTENTLY REGISTER ANNOYANCE; SOME HEAR THE MACHINE BUT ARE NOT BOTHERED
- THE MAJOR ANNOYANCE APPEARS TO BE THE REPETITIVENESS OF THE SOUND, NOT THE AMPLITUDE OR TONE

SOUND GENERATION

MOD-1 SETTING AT BOONE, NORTH CAROLINA

- BOONE IS IN A VALLEY IN HILLY WOODED TERRAIN
- MACHINE IS ON THE SUMMIT OF A TREE-COVERED HILL AT AN ELEVATION OF 1350 METERS, 300 METERS ABOVE THE CITY OF BOONE, NORTH CAROLINA
- THE AFFECTED HOMES ARE IN SMALL VALLEYS SURROUNDING THE SITE, WITHIN 1.5 KM OF THE MACHINE, IN QUIET, WOODED SETTINGS
- NO COMPLAINTS HAVE BEEN RECEIVED FROM HOUSEHOLDS IN THE CITY OF BOONE

SOUND GENERATION

MOD-1 SOUND INVESTIGATIONS

- OBJECTIVE: TO REDUCE OR ELIMINATE THE ANNOYING SOUNDS.

- APPROACH: FORM A TEAM TO INVESTIGATE SOUND GENERATION & PROPAGATION.
  - -- ANALYTICAL STUDIES
    - ADAPT EXISTING PROPELLER-SOUND MODELS TO WTS
    - STUDY EFFECTS OF WIND SPEED GRADIENTS, TURBULENCE, AND TOWER SHADOW ON SOUND GENERATION
    - IDENTIFY SOURCE & MECHANISM OF THE ANNOYING SOUNDS
    - STUDY EFFECTS OF TERRAIN, GROUND CLUTTER, TURBULENCE, TEMPERATURE GRADIENTS, STRATIFICATION & OTHER ATMOSPHERIC EFFECTS ON SOUND PROPAGATION
    - PREDICT WHICH AREAS ARE MOST LIKELY TO BE AFFECTED

SOUND GENERATION

MOD-1 SOUND INVESTIGATION (CONTINUED)

-- EXPERIMENTAL STUDIES

- PERFORM NEAR & FAR FIELD MEASUREMENTS AT MOD-1 SITE
- PERFORM SUPPORTING MEASUREMENTS AT MOD-0 SITE, WITH BOTH UPWIND AND DOWNWIND ROTOR CONFIGURATIONS
- CONDUCT LABORATORY SCALE EXPERIMENTS
- MAKE MEASUREMENTS AROUND SMALL WTS (LESS THAN 100 KW AND 30 METER DIAMETERS

SOUND GENERATION

MOD-1 SOUND INVESTIGATION (CONTINUED)

TENTATIVE ANALYTICAL FINDINGS:

- SOUND LEVELS AT FREQUENCIES BELOW 20 HZ (INAUDIBLE) ARE PREDICTED TO BE WELL BELOW THE ANNOYANCE THRESHOLD
- THE BLADES/TOWER-WAKE INTERACTION IS THE PRIMARY SOURCE OF SOUND GENERATION
- SOUND LEVEL-TIME SIGNATURES FOR SIMPLE WAKE FLOW MODELS ARE QUALUITATIVELY SIMILAR TO MEASURED SIGNATURES
- PREDICTED SOUND LEVELS IN THE AUDIBLE LOW FREQUENCY RANGE OF 20 TO 100 HZ ARE IN APPROXIMATE AGREEMENT WITH MEASURED LEVELS
- PRESENT SOUND GENERATION MODELS NEED FURTHER REFINEMENT & VALIDATION WITH MEASURED DATA
- ATMOSPHERIC CONDITIONS AND TERRAIN CONTOUR CAN INTENSIFY SOUND LEVELS BY REFLECTIONS AND DEFRACTION AND ALSO PROPAGATE THE SOUND TO AREAS BEYOND THE LINE OF SIGHT FROM THE MOD-1

SOUND GENERATION

MOD-1 SOUND INVESTIGATIONS (CONTINUED)

TENTATIVE - EXPERIMENTAL FINDINGS:

- THE FUNDAMENTAL FREQUENCY OF THE ROTOR SOUND IS EQUAL TO THE BLADE PASSING FREQUENCY (2P)
- THE AUDIBLE "THUMPING" SOUND IS COMPOSED OF HIGHER HARMONICS IN THE FREQUENCY RANGE 20 TO 50 HZ
- SOUND LEVELS AT FREQUENCIES BELOW 20 HZ ARE WELL BELOW THE ANNOYANCE THRESHOLD
- THE SOUND-TIME SIGNATURES & THE FREQUENCY SPECTRUM VERIFY THAT THE BLADE PASSAGE THRU THE TOWER WAKE IS THE PRIMARY SOURCE OF THE THUMPING SOUND. THE SPECIFIC MECHANISM INVOLVED IS UNDER INVESTIGATION
- OPERATING THE MOD-0 & MOD-1 AT LOWER RPM LEADS TO A REDUCTION OF THE SOUND LEVEL BUT THE THUMPING NATURE PERSISTS
- OPERATION OF THE MOD-0 WITH THE ROTOR UPWIND OF THE TOWER APPEARS TO CHANGE THE NATURE OF THE SOUND

App. I: presentation
J. M. Savino "Sound Generation"

NASA Technical Memorandum 81813

SOME CALCULATED EFFECTS OF NON-UNIFORM INFLOW ON THE RADIATED NOISE OF A LARGE WIND TURBINE

George C. Greene and Harvey H. Hubbard

May 1980

National Aeronautics and
Space Administration

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SOME CALCULATED EFFECTS OF NON-UNIFORM INFLOW ON THE RADIATED NOISE OF A LARGE WIND TURBINE

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Hampton, Virginia

INTRODUCTION

The operation of large wind turbines such as the one shown in Figure 1 may become commonplace in the future as an alternate source of energy (refs. 1 and 2). Because of particular constraints regarding their locations and schedules for efficient operation, there is concern for adverse community impact due to noise.

Since the rotor-support tower configuration can in some cases be a dominant factor in noise generation, the current study was performed to evaluate the potential noise problems of configurations in which the rotor is located downwind of the support tower. In such configurations, the tower structure can interfere with the inflow to the rotor and can thus result in a non-uniform circumferential disk loading. In order to evaluate such an effect, application was made of a recently documented computer program for the calculation of noise from advanced propellers (ref. 3). This program which is based on a numerical technique for implementing the theory of reference 4, produces results in both the time and frequency domain and is applicable to noise prediction from large distributed sources such as a propeller disk over which the aerodynamic loading is a variable.

The purpose of this paper is to present the results of noise calculations for which the loading around the circumference of the rotor disk varied in a manner simulating two types of tower wake deficiencies and to compare these results with similar noise calculations for a uniform disk loading case.

APPARATUS AND METHODS

Some of the specifications of the example wind turbine for which calculated noise data are presented are given in Table I. It is a 2000 KW capacity machine which consists of a two-blade 61 meter (200 ft.) diameter rotor mounted on a 42.7 meter (140 ft.) truss type tower. The rotor is mounted so that the inflow first encounters the tower structure, and then enters the rotor disk. The blades are linearly tapered in chord, are twisted along the span, and operate with variable pitch to control the rotor

(2)

speed at 35 rpm. The estimated steady loading patterns along the blade chord and span which were used for all calculations are shown in Figure 2. The circumferential load distributions for the rated turbine output power were approximated in two ways for the cases where the inflow to the rotor disk was interrupted by the support tower wake and are shown in Figure 3, b and c. A uniform circumferential load distribution was assumed for the baseline cases without tower wake (fig. 3a).

Radiated Noise Calculations

Noise calculations for far field conditions around the wind turbine have been made by means of a modified version of the Farassat/Nystrom propeller noise prediction program described in Reference 3. The program properly accounts for the significant geometry features of the rotor, its operating conditions, and the non-uniform distribution of aerodynamic loading over the rotor disk. It is particularly useful for the studies of this paper which were made for the evaluation of the effects of ingestion by the rotor of the tower wake which contains velocity deficiencies.

RESULTS AND DISCUSSION

Calculations were made for field points 1,000 meters distant and for a range of azimuth angles in a plane 300 meters below the hub of the wind turbine (see fig. 4) which is assumed to be located on a hill. Instantaneous acoustic pressure time history, frequency spectra, and directivity information were calculated and are summarized in data Figures 5-7.

Instantaneous Pressure Time Histories

Figure 5 presents the calculated pressure time history at the $\alpha = 0°$ location and for three operating conditions, namely: the case for uniform inflow to the disk for which there is no tower strut interference, and then two cases for different tower strut interference models. The associated pressure time histories for one blade passage for each case are shown. For the uniform inflow case (fig. 5a), the blade passage pulse is minimal and cannot be observed when plotted at this scale. For the single loading notch case (fig. 5b), the calculated signature has negative and positive peaks separated in time by an amount related to the width of the notch. Likewise, the peak amplitudes are related to the depth of the notch. On the other hand, the bottom trace (fig. 5c), resulted from an assumed double notch inflow pattern which would represent the flow around the large corner members of the truss structure. The resulting time history pattern resembles some that have been observed for large wind turbines and there is thus reason to conclude that the bottom loading pattern is representative of the loading in the example installation.

Frequency Spectra

The corresponding frequency spectra calculations are shown in Figure 6. Computations were carried out for the first 50 harmonics of the blade passage frequency and the results are shown for each of the circumferential loading

(3)

conditions of Figure 3. The most obvious result is that the spectrum for the uniform inflow case (blocked-in circle symbol) contains only a single harmonic of significant amplitude; all others being off scale at the bottom. The notched loading cases on the other hand both produce significantly higher fundamental components and in addition there are many strong harmonics in the frequency range up to at least 60 Hz. This result suggests that a configuration for which the tower interference is minimized would have markedly more favorable noise characteristics. A comparison of the two spectra for the notched loadings reveal no significant differences due to notch details. Thus it may be concluded that the presence of flow deficiencies is a major function in the noise produced, whereas the details of such deficiencies may be of only secondary importance.

Directivity Pattern

In order to define some of the directivity characteristics of the wind turbine noise, a series of calculations were made for the double notched loading condition and over the range of azimuth angles indicated in Figure 4. These far field noise results are shown for comparison in Figure 7. Calculated spectra are presented at three different azimuth angles along with the associated overall noise levels. For the case indicated the overall levels vary from 72.9 dB at the 0° location and 70.2 dB at the 45° location down to 59.7 dB at 90°. The relatively high levels that are indicated down wind and near the axis of rotation result at least in part from the assumed asymmetric loading. A comparison of the associated spectra indicate that the levels of the lowest order harmonics are comparable and that the differences in the overall levels results mainly from differences in the levels of the higher harmonics.

CONCLUDING REMARKS

Computations by the Farassat/Nystrom method indicate that for the uniform inflow case, a large wind turbine generated relatively low noise levels and the first rotational harmonic dominated the spectrum. On the other hand, cases incorporating wake flow deficiencies from the upstream support tower structure indicate substantially increased noise levels for all harmonics; the greatest increases being associated with the higher harmonics.

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TABLE I

2000 KW WIND TURBINE SPECIFICATIONS

Rotor	
No of Blades	2
Diameter	61 (200)
Speed, RPM	35
Pitch	variable
Cone angle, Deg	9
Tilt Angle, Deg	0
Location relative to tower	downwind
Direction of Rotation	Counterclockwise (looking upwind)
Blade	
Length, m (ft)	30 (97)
Weight/Blade, Kg (lb)	9800 (21,500)
Airfoil	NACA 44XX
Root Chord, m (ft)	3.7 (12)
Tip Chord, m (ft)	0.85 (2.8)
Chord Taper	Linear
Tower	
Type	Pipe truss
Hub Height Above Ground, m (ft)	43 (140)

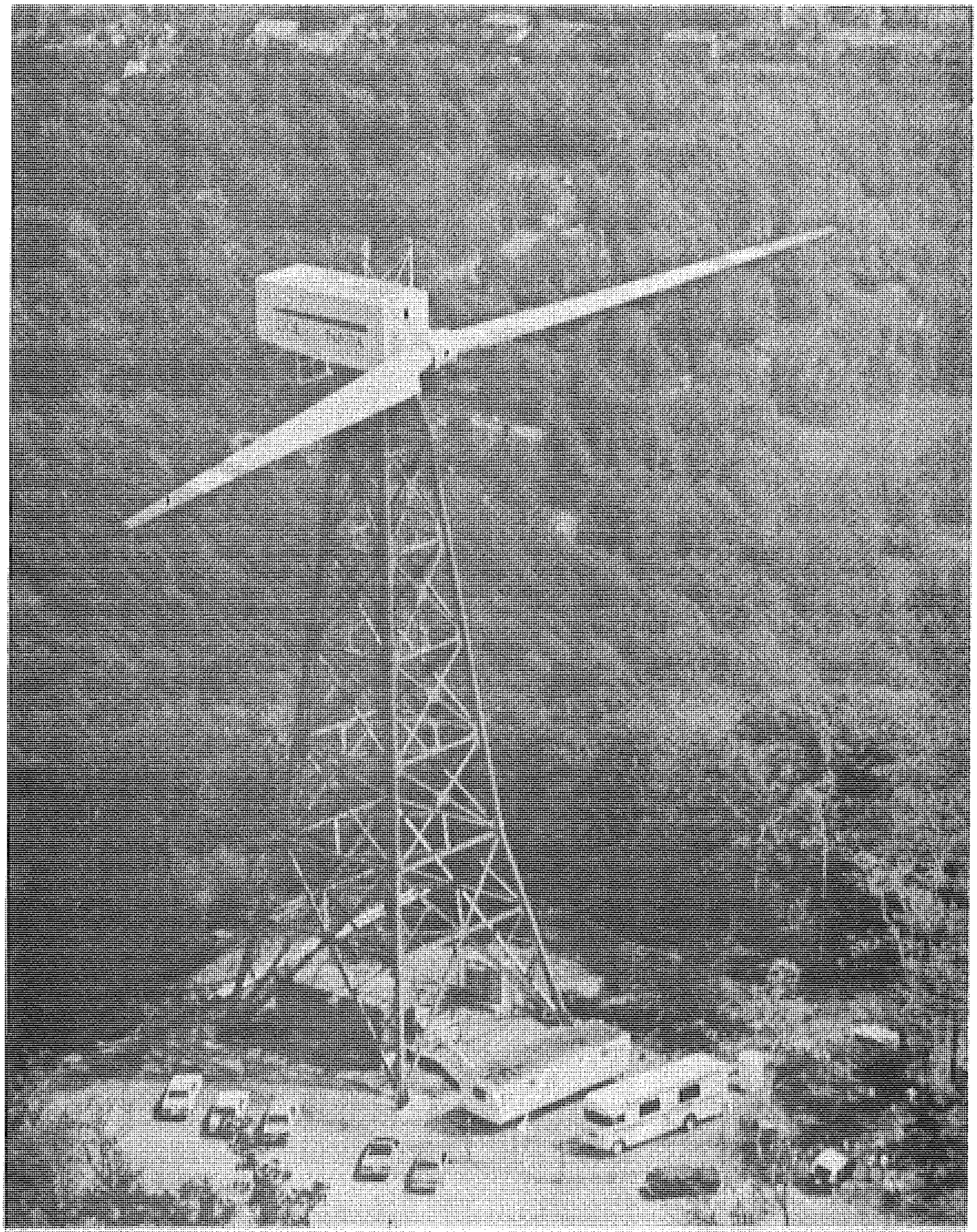

Figure 1.- DOE/NASA 2000 KW Experimental Wind Turbine

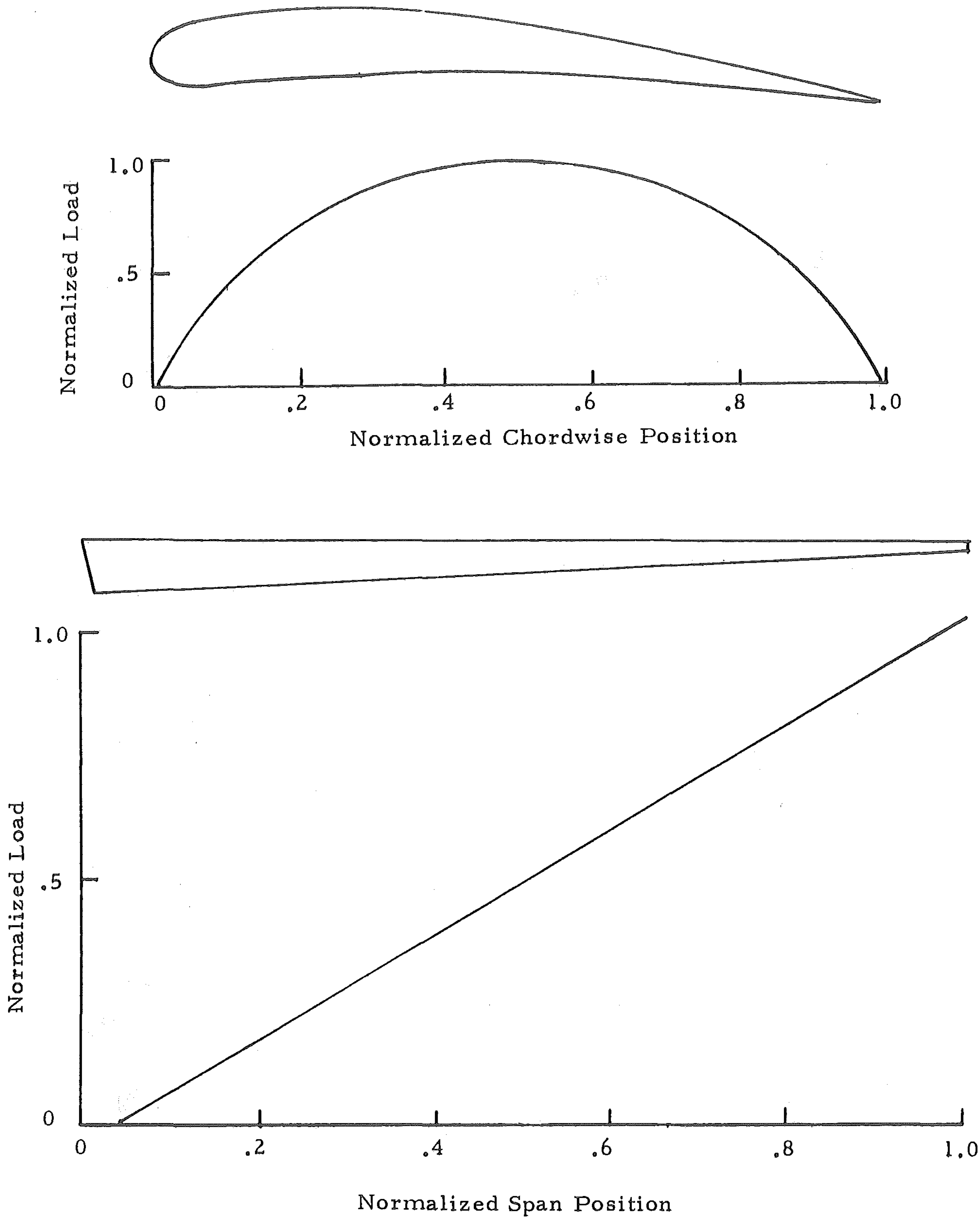

Figure 2.- Assumed Spanwise and Chordwise Aerodynamic Load Distributions for Wind Turbine Rotor Blades

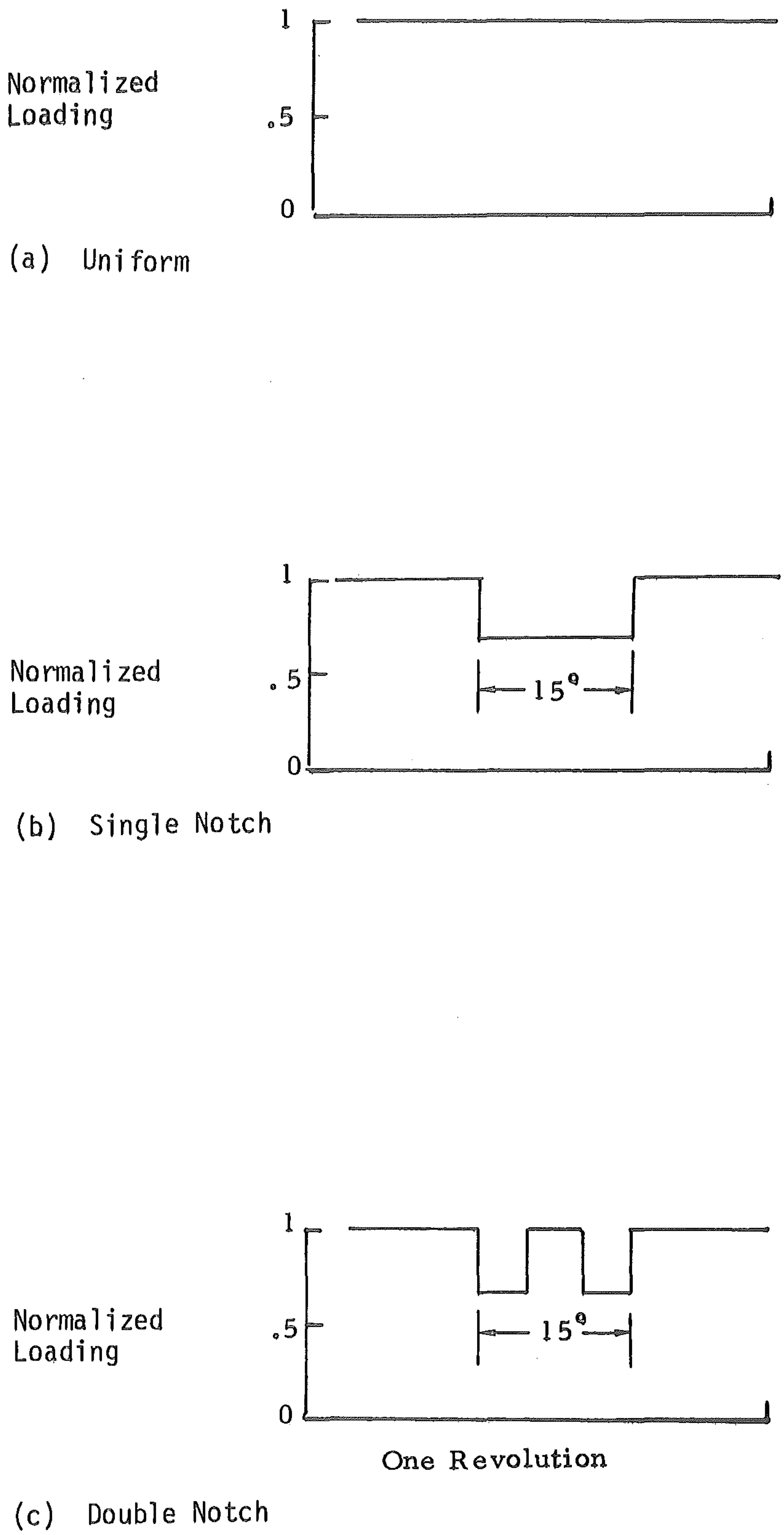

Figure 3.- Assumed Circumferential Load Distributions Around the Rotor Disk for Constant Absorbed Power.

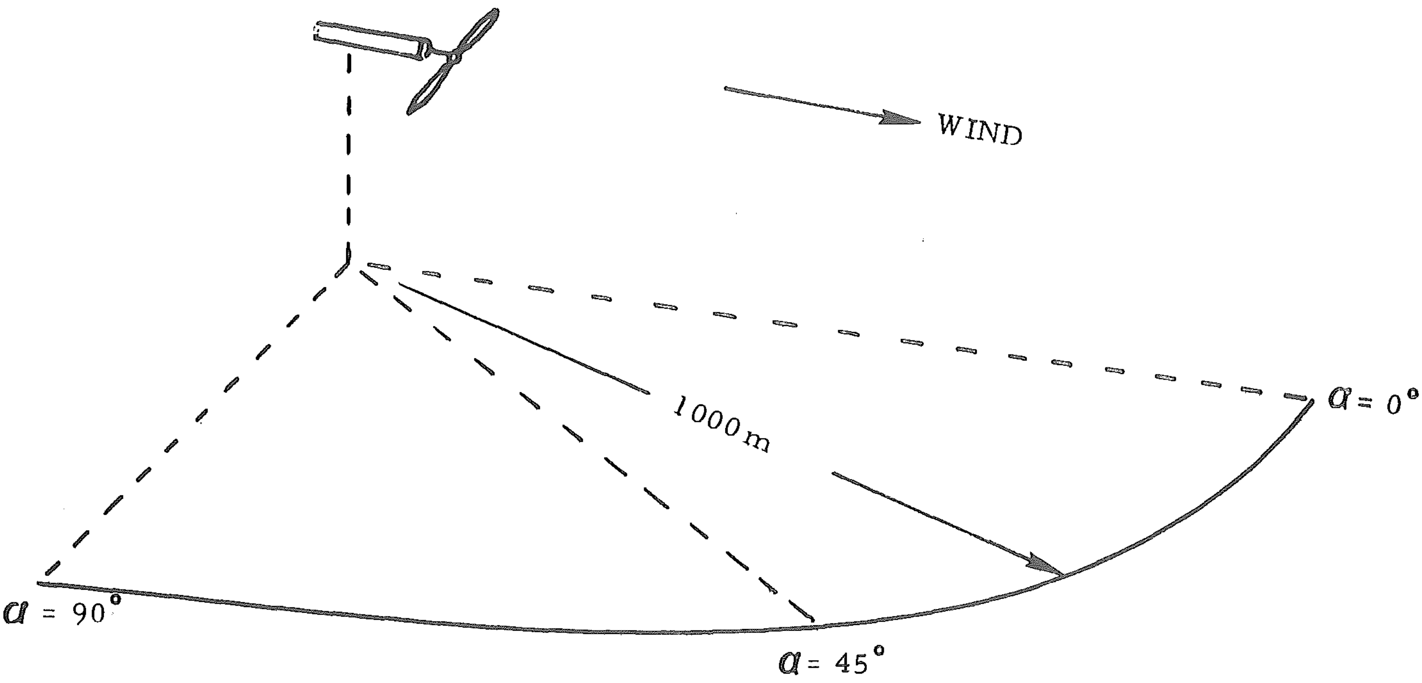

Figure 4.- Coordinate System for Far Field Noise Calculations

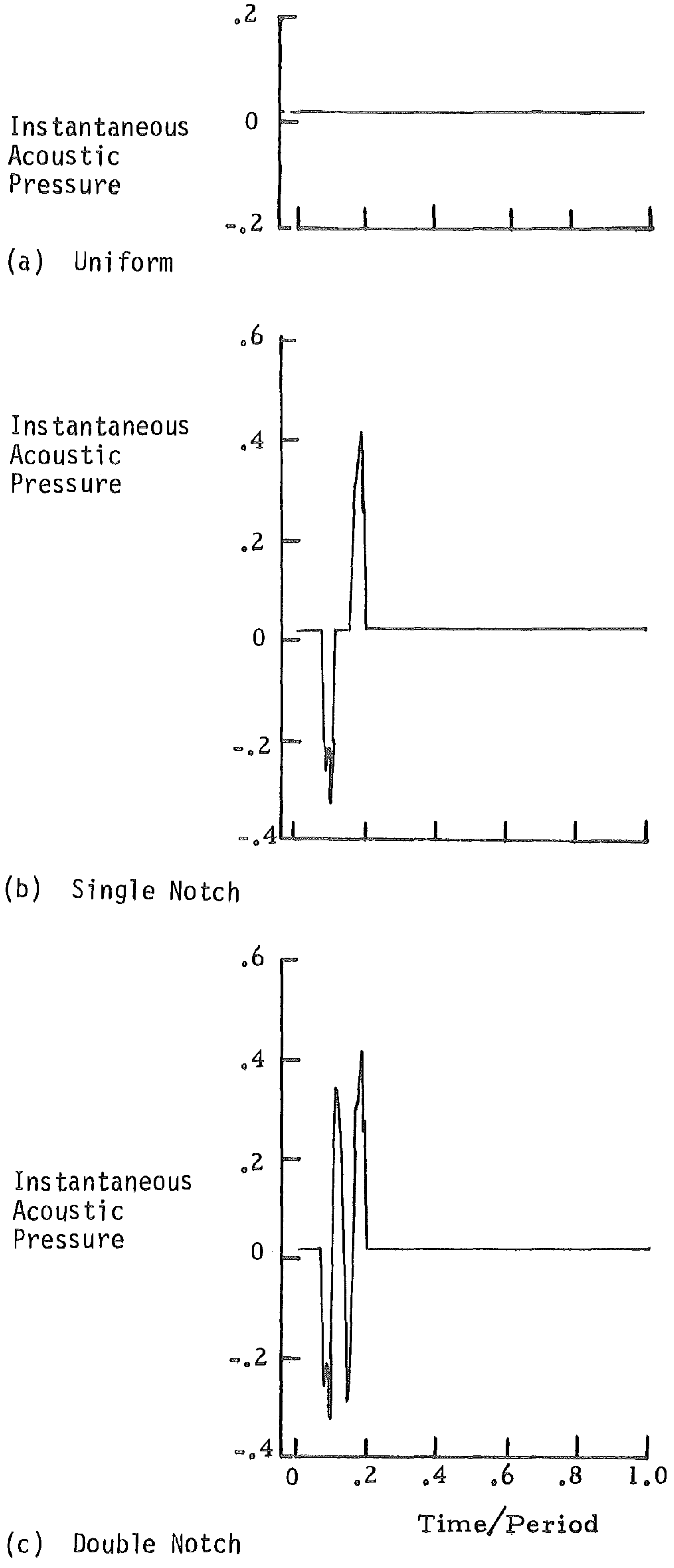

Figure 5.- Calculated Far Field Noise Time Histories For Three Different Blade Loading Patterns. $\alpha = 0°$, Distance = 1,000m

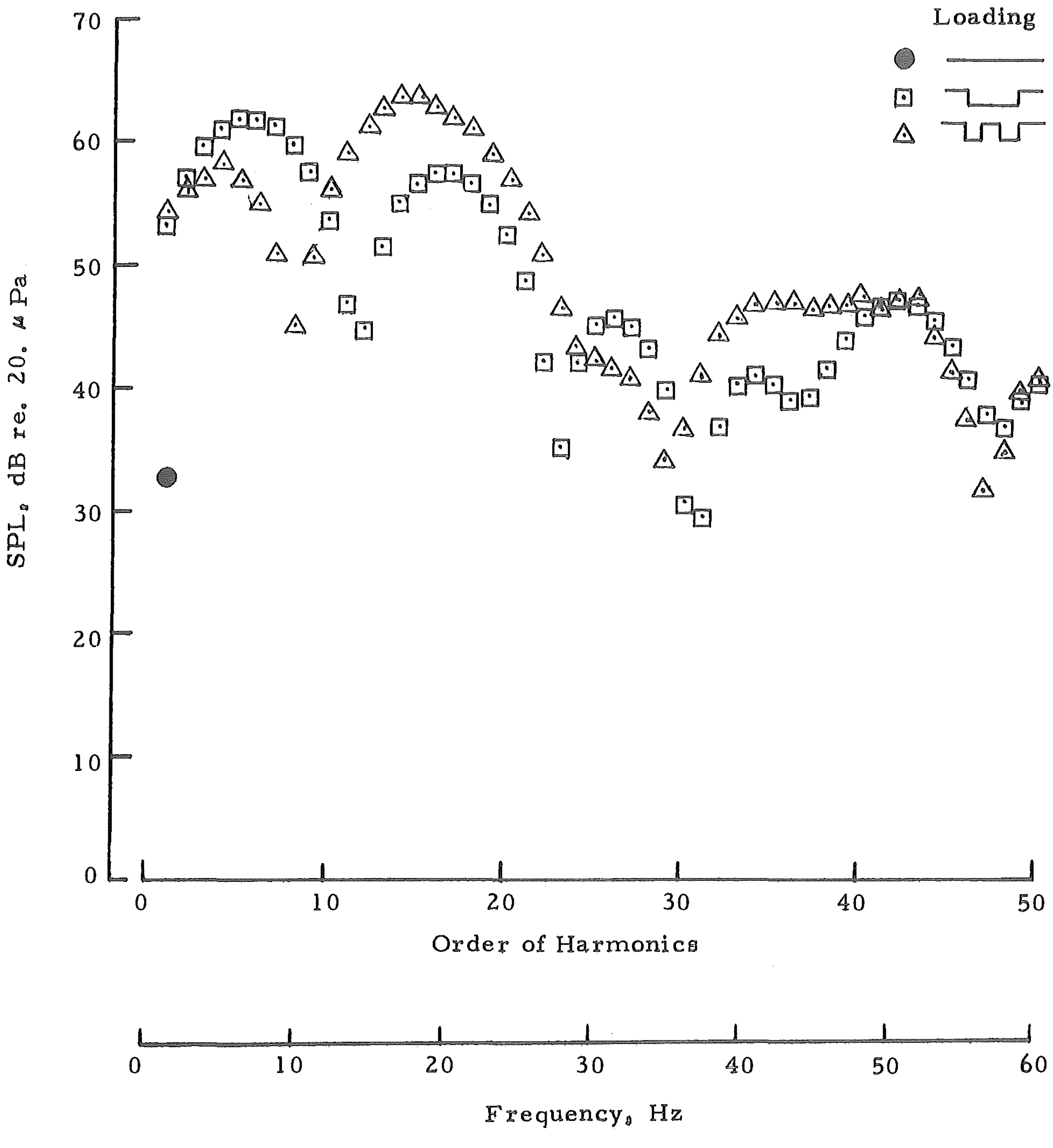

Figure 6.- Calculated Far Field Noise Levels as a Function of Order of the Harmonic for Three Different Loading Patterns, α = 0°, Distance = 1,000 m

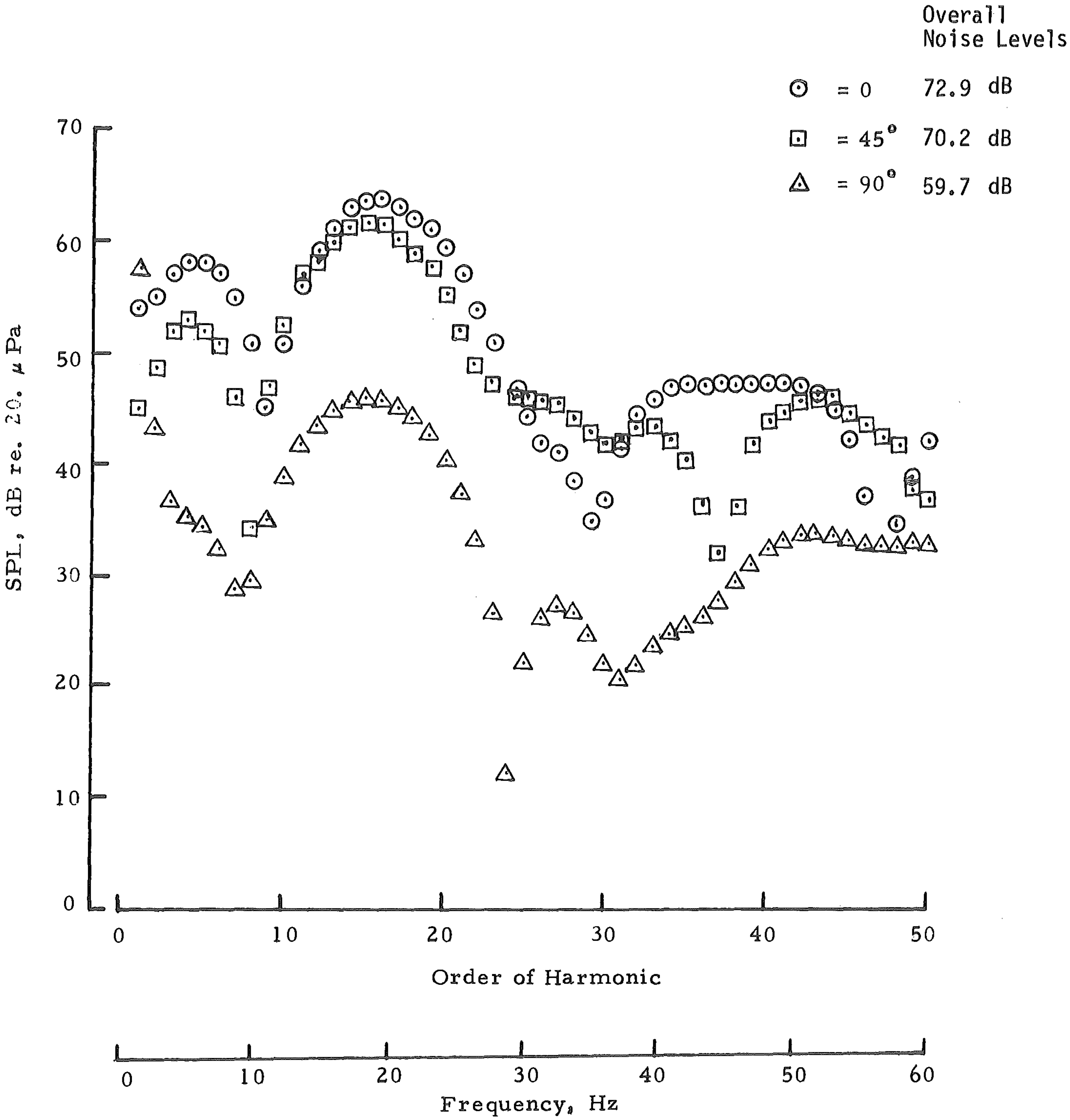

Figure 7.- Calculated Far Field Noise Levels as a Function of Order of the Harmonic for Three Different Azimuth Angles and for a Double Notched Load Distribution. Distance = 1,000m.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-81813		

4. Title and Subtitle	5. Report Date
Some Calculated Effects of Non-Uniform Inflow on the Radiated Noise of a Large Wind Turbine	May 1980
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
George C. Greene and Harvey H. Hubbard	
	10. Work Unit No.
9. Performing Organization Name and Address	505-32-03-03
NASA Langley Research Center Hampton, Virginia 23665	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D. C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Far field noise computations have been performed for a large wind turbine to evaluate the effects of non-uniform aerodynamic loading over the rotor disk. A modified version of the Farassat/Nystrom propeller noise prediction program was applied in order to account for the variations in loading due to inflow interruption by the upstream support tower.

The computations indicate that for the uniform inflow case, relatively low noise levels are generated and the first rotational harmonic dominated the spectrum. For cases representing wake flow deficiences due to the tower structure, substantially increased noise levels for all harmonics were indicated, the greatest increases being associated with the higher order harmonics.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Wind turbines, noise generation, theoretical calculations	Unclassified - Unlimited Subject Category 71

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
UNCLASSIFIED	UNCLASSIFIED	12	$4.00

* For sale by the National Technical Information Service, Springfield, Virginia 22161

App. II: presentation
J.M. Savino "Sound Generation"

NASA Technical Memorandum 81486

AN EXPLORATORY SURVEY OF NOISE LEVELS ASSOCIATED WITH A 100 kW WIND TURBINE

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Prepared for the
Ninety-ninth Meeting of the Acoustical Society of America
Atlanta, Georgia, April 21-25, 1980

AN EXPLORATORY SURVEY OF NOISE LEVELS ASSOCIATED WITH A 100 kW WIND TURBINE

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ABSTRACT

During performance tests of a 125-foot diameter, 100 kW wind turbine at the NASA Plum Brook Station near Sandusky, Ohio, the opportunity arose to make exploratory noise measurements and results of those surveys are presented. The data include measurements as functions of distance from the turbine, and directivity angle, and cover a frequency range from 1 Hz to several kHz. Potential community impact is discussed in terms of A-weighted noise levels relative to background levels, and the infrasonic spectral content. Finally, the change in the sound power spectrum associated with a change in the rotor speed is described. The acoustic impact of this size wind turbine is judged to be minimal.

INTRODUCTION

Wind turbines have recently attracted considerable interest as a way of generating additional electricity, while avoiding the adverse environmental impact characteristic of conventional power plants. These wind turbines, however, have their own potentially adverse impact on the environment, that of producing noise. In respone to future needs, there is likely to be an increasing use of wind turbines in both larger and more numerous installations. Experience with small wind turbines such as used on farms, indicates that the noise level of these devices is rather low. For larger installations designed for utility use, this may not be true. the evaluation of the possible wind turbine environmental impact is difficult at present since only a small amount of information is available about the level and propagation of wind turbine sound (ref. 1). To predict the sound levels of future wind turbine designs, information describing wind turbine acoustic characteristics is required. This paper presents data and an analysis of the noise associated with a 100 kW wind turbine.

EXPERIMENTAL APPARATUS AND PROCEDURE

Wind Turbine

To determine wind turbine acoustic characteristics, exploratory measurements were made on a 38 m (125 ft) diameter, 100 kW wind turbine (ref. 2), located at NASA's Plum Brook Station near Sandusky, Ohio. For several years this facility has been used to evaluate the operating characteristics of a number of wind turbine configurations. Figures 1 and 2 present views of the two configurations in which the wind turbine was operated during two series of acoustic field surveys.

The first series is associated with the installation shown in figure 1, which used full span airfoil blades. For this test series, the wind turbine was operated at 40 rpm, and with the wind available during the test period, generated 30-40 kW. The second test series is associated with the installation shown in figure 2, which used part span airfoil blades. For this test series, the wind turbine was operated at 33 and 26 rpm, and with the winds available on the two test days it generated abut 60 kW. Regardless of the choice of rotor rpm, by means of a variable gear ratio, the wind turbine generator speed was controlled to generate power at 60 Hz. During both test series, the wind turbine was oriented with the blades downwind of the support tower.

Records of operating conditions from the first test series are shown in figure 3. These records are typical of both test series. Wind speed and direction changed significantly during the testing, making the quoted power levels only nominal. Figure 3 indicates a wind speed variation of 10-30 km/hr mph over a few minutes, and wind direction variation of about 40°. The corresponding power level varied approximately from 0 to 100 kW design value.

Acoustic Measurements

For the first series of acoustic tests, the microphones used to measure the wind turbine noise were located as shown in figure 4. The instrumentation associated with these microphones was mounted in a small van located as shown in this figure. Two microphones were used, Bruel & Kjaer models 4133 of 1.2 cm (0.5 in) diameter and 4161 of 2.5 cm (1 in) diameter. These condenser microphones, both protected by windscreens, had a flat frequency response down to approximately 10 Hz. The low-frequency response corrections that were used were not the same for the two instrumentation channels because of the differences in sensitivity of the two microphones. The applicable corrections are listed in table 1. These tabular values are corrections for all equipment errors, and were determined partially by reference to manufacturers literature and partially by experimental evaluation of these units. For this series, as well as the second test series, the microphones were located about 1.8 m (6 ft) above ground level. For this first test series, the 2.5 cm diameter microphone (M1 in fig. 4) was used as a survey microphone at 30, 61 and 122 m (100, 200, and 400 ft) distances at about 120° from the wind turbine's upwind axis. The 1.2 cm diameter microphone (M2 in fig. 4) was fixed at 61 m (200 ft) from the wind turbine at approximately 40° from the wind turbine upwind axis. These same microphones were also used to record the ambient noise at these locations for comparison with wind turbine sound levels.

For the second series of acoustic tests the measurement locations were as identified in figure 5. For these measurements, two surveys in the azimuthal direction around the wind turbine were made. The first survey was made during operation at 33 rpm, and the second during operation at 26 rpm. Additional acoustic instrumentation was available for this test series. Consequently four microphones were used to obtain data for the 10 positions required. These 10 positions were 61 m (200 ft) from the wind turbine at angles from 0° to 180° in 20° increments. The four instrumentation channels were scheduled so that one was used for 0°, 60°, and 120°, a second for 20^{o}, 80^{o} and 140^{o}, a third for 40^{o}, 100^{o} and 160^{o}, and the fourth for 180_{o}. In this test series, only model 4133 1.2 cm (0.5 in) diameter microphones were used.

Apparatus inaccuracies, particularly at low frequencies, influence the data accuracy. Most acoustic measuring equipment is designed for the audio range of 20 Hz to 20 kHz. This equipment (microphones, preamplifiers and amplifiers) consequently has a severely degraded accuracy in the 0.1 to 20 Hz infrasonic range. For this program, the decision was made to use conventional acoustic equipment and to attempt to compensate for the reduced frequency response.

In addition to the low frequency inaccuracies, there may also be high frequency limits to spectral accuracy. Limitations in the dynamic range of tape recorders restrict the amplitude range of data that can be recorded for analysis. High frequency amplitude limits occurred because the wind turbine high frequency sound levels, when recorded, were comparable to, or less than, those of the tape recorder noise. For this noise survey, the usable frequency range was limited to approximately 1-3000 Hz. Figure 6 illustrates the characteristics of the tape recorder noise floor.

Data Presentation

The bulk of the acoustic data presented was produced by analyzing the recorded data using constant bandwidth filters. The resulting presentation is that of sound pressure level as a function of the log of frequency, with a nominally 1 Hz (actually about 1.3 Hz) bandwidth. To obtain this frequency resolution, each data sample was analyzed over 0 - 130 Hz, 0 - 1300 Hz and 0 - 13 000 Hz ranges, and then portions of each of the three plotted analyses combined to form plots over four decades of frequency, 1-10 000 Hz. This involved combination of spectra was done in an attempt to maximize resolution and normalize spectra to a 1 Hz bandwidth.

The final sound pressure level figures combine the 1 - 10 Hz decade of the first range, 10 - 100 and 100 - 1000 Hz decades of the second range, and the 1000 - 10 000 Hz decade of the third range. The final resolution was made the same as that of the original 10 - 1000 Hz decades. To make the levels of the 1 - 10 Hz and 1000 - 10 000 Hz decades compatible with the 10 - 1000 Hz decades, a change is required. The factor of 10 times the log of the ratio of frequency resolutions was used to correct the broadband spectrum levels for the change in display bandwidth. Use of this factor results in adding 10 db to the levels of the 1 - 10 Hz portion, and in subtracting 10 db from the levels of the 1000 - 10 000 Hz decade. The tone levels, when initially clearly resolved, are unaffected by analysis bandwidth and consequently remain at their original amplitudes.

Test Limitations

Several limitations are present in making meaningful and accurate noise measurements on wind turbines. One limitation may be simply the relatively close microphone locations that were used in comparison with the size of the noise source. In general, at distances which are relatively small the sound level will not decrease with the inverse square of the distance. If the diameter of the wind turbine, 38 m (125 ft), is used as the size of the noise source, then the microphones should be much farther than 38 m (125 ft) for the wind turbine to act as point source with the microphone in the geometric far field. Another limitation arises from the low frequency nature of the wind turbine noise. At the measurement points, the microphones were less than one wavelength away for frequencies less than 5-10 Hz, which have wavelengths of 30-60 m. At frequencies or distances greater than this (acoustic far field) the sound pressure characteristics of the wind turbine are more fully developed.

There are other limitations, particularly at low frequencies. As is true for most turbomachinery, the highest spectral levels are at the blade passage frequency; the wind turbine's low speed of rotation and small number of blades result in a blade passage frequency near 1 Hz. Pressure levels at these low frequencies could be subject to errors either from wind effects or from the equipment limitations previously discussed. The noise or turbulence due to the wind blowing over obstacles in the vicinity would be expected to be predominantly at low frequency. In addition, wind blowing over the microphones themselves can create noise at low frequence, and there may be aerodynamic pressure fluctuations or pseudo sound generated. Each of these wind noise sources may vary in intensity with the wind speed and direction.

RESULTS AND DISCUSSION

First Test Series

The results of the radial survey of wind turbine noise levels will be presented first followed by the results of the azimuthal surveys.

The radial survey measurements offer potential answers to several questions. One question is how much noise is generated by the wind turbine. Since the degree to which a wind turbine may affect a community's environment is a consideration, the annoyance reponse A-weighting scale was used in evaluating sound level. This scale weights most heavily the levels at frequencies near 1000 Hz for which hearing response is most sensitive. Figure 7 presents A-weighted sound levels measured by the fixed microphone 61 m (200 ft) from the wind turbine. To produce this figure, six data samples, approximately 6 minutes long, were recorded and analyzed into several 30 second averages. The upper three clusters of points result from A-weighting the noise of the wind turbine while operating at about a third of its design power. The lower three clusters of point result from A-weighting the background noise at the same location. At 61 m (200 ft), the wind turbine sound level was 60 dBA, with approximately 1 db scatter. At the same location, the background level was approximately 48 dBA, with a scatter between 2 and 10 db between 30 second periods. For comparison, 50 dBA is the sound level in a typical residential area, while 60 dBA is representative of levels inside large retail stores.

Another question of interest about wind turbine noise is how the sound level changes with distance. Figure 8 presents the A-weighted sound levels from the survey microphone (designated M1 on fig. 4). Since the survey and fixed microphone data were taken simultaneously, the three background noise points at 30, 61 and 122 m (100, 200 and 400 ft) distances were taken during the background test points of figure 7, respectively, and the corresponding wind turbine data points were taken in similar fashion. As was the case for the fixed microphone (M2) data, there is about a 1 db scatter in the 30 sec. averages of wind turbine sound levels, but a decrease in level clearly exists. The level changes from 63 dBA at 30 m (100 ft) to 60 dBA at 61 m (200 ft) and then to 54 dBA at 122 m (400 ft). The attenuation slope changes at 61 m (200 ft) from about 3 db per doubling of distance at closer locations to 6 db per doubling of distance at farther locations. This decrease of the A-weighted level indicates that by 60 meters (200 ft) far field distances have been reached for audio frequencies. In considering community response to the noise propagated from this wind turbine, it should be noted that the data at 122 m (400 ft) distance indicate a wind turbine sound level nearly equal to the background sound level. Figure 9 presents averages of the previous survey microphone data, and more clearly shows the decrease of wind turbine noise with distance. When these microphone data were extrapolated to greater distances, the wind turbine and background levels became equal at about 183 m (600 ft).

Thus far, the results of the radial survey of wind turbine noise have been presented in terms of A-weighting which emphasizes the impact of audio frequencies near 1000 Hz. Further results will be presented as unweighted spectra from 1 Hz to slightly over 2 kHz. The associated pressure has rather coarse resolution because of the large range of amplitudes that are displayed. Figure 10, which displays wind turbine noise spectra at three distances and the background noise, shows a decrease with distance for frequencies greater than about 100 Hz.

The large number of tones in the wind turbine noise spectra at frequencies greater than 100 Hz were not identified as to origin, but are presumably associated with mechanical components of the wind turbine power train. Those tone frequencies which are common with the background are most likely due to extraneous noise sources at the test site or in the instrumentation.

There is some evidence of tones at multiples of blade passage frequency, at approximately the background level. It was expected that the noise characteristics of the wind turbine would include these low frequency tones because in typical turbomachinery spectra, blade passage frequency harmonics are very obvious and influential components. It was expected that despite the smaller number of blades and lower speed of a wind turbine, compared with more conventional turbomachinery, these discrete frequency tones would still appear. These tones do appear, but at relatively low levels. Somewhat unexpected is the appearance of an amplitude envelope around these tones (fig. 11) which is a pattern characteristic of a repeated impulse rather than of a sinusoidal disturbance. In this test series, the blades were located downwind of the turbine tower, so a likely source of this periodic impulse noise is the interference of the tower wake with the blades. This source identification seems likely for the following reason. The time period of this disturbance may be estimated as the inverse of the interval of the tone envelope (10 Hz). Therefore, the period of time that a wake interferes with the blades would be approximately 0.1 second for this first test series (for which the wind turbine speed was 40 rpm). At an effective point of 70% of the blade span, this 0.1 second period corresponds to the time required for a blade to pass through a wake as wide as the tower. Consequently, it is likely that the source of the low frequency tones is the interference of the support tower wake with the blades.

The low-frequency spectrum levels are nearly the same at each measurement point. One possible reason for this is the fact that the microphone locations are in the acoustic near field. Another possibility is that the blade passage frequency interaction tone may be so low in amplitude that the background noise predominates. Figure 11 presents spectral data from 1-20 Hz for wind turbine sound at 30 m (100 ft) and 122 m (400 ft) and also the background level. A 0.03 Hz bandwidth was used to better resolve the tones, and the curves were offset by 10 db to avoid confusion. Apparently, while the tones decrease an average of 9-10 db between the two locations, the broadband level is independent of location. The broadband level is essentially the background level. A further comment can be made about the levels in this frequency range. These low frequencies are outside the audio range, but pressures at these frequencies may be sensed if the levels are high enough. The threshold of human annoyance, or even psychological damage is not well defined, but one reported threshold of annoyance to infrasound is a sound pressure level of 120 db at frequencies less than 5 Hz, decreasing to 90 db at 20 Hz (ref. 3). These particular levels were not exceeded or even approached during the reported wind turbine testing.

Second Test Series

The second test series explored the effects of speed on the wind turbine sound level and surveyed the sound field as a function of angle. These measurements of wind turbine noise were made on a 61 m (200 ft) radius at 26 and 33 rpm, using the configuration shown in figure 2, with microphones located as shown in figure 5. The results, as displayed in figure 12 as individual microphone location spectra, are generally higher in amplitude than the data from the first series. Several differences exist between the two test series; among them are blade shape, turbine power level and wind speed. The specific reason for the data difference is not known, and no further comparison with the radial survey data will be made.

The wind turbine noise level differences between operation at 26 rpm and 33 rpm are mainly at the upwind angles, 0° - 40°. These differences, shown for 0° though 180° in 20° increments, increase with frequency, independent of angle. This difference as a function of frequency is seen more clearly in figure 13, which presents estimates of the wind turbine sound power levels at 61m for the two speeds. These data, like the sound pressure level data, are presented on a log frequency scale with a frequency bandwidth of 1 Hz. The difference in estimated wind turbine sound power between opration at 26 rpm and 33 rpm increased from about 3 db at 1 Hz to 16 db at 1000 Hz. A prediction of the amount of the increase, based on a 6th power dependency of noise level on speed, would be 6 db. If the differences in power level of figure 13 are integrated over the frequency range, the mean difference between total power levels is slightly over 5 db -- fair agreement with a 6th power relationship.

To some extent, the power level data at frequencies less than about 100 Hz are only estimates. The true power level should be independent of distance from the wind turbine. Since these low frequency pressures do not decrease with the square of distance (fig. 10), the computed power levels will be a function of distance. The power level values presented here are determined from the measurements at 61 m (200 ft).

In addition to the exploration of noise trends with speed, the variation of wind turbine sound pressure level with angle was explored. To do this, the spectral data of figure 12 were plotted against angle in figures 14 and 15 for 26 and 33 rpm, respectively. Results are shown for 2, 10, 100, 200 and 500 Hz. The 2 and 10 Hz frequency levels show high amplitudes with nearly omnidirectional characteristics except for a 5 - 10 db lobe in the downwind quadrant. The 2 and 10 Hz data are probably near-field data, while the pressures at higher frequencies have the more lobular far-field propagation characteristics. The 100 and 200 Hz levels show directivity peaks in both upwind and downwind quadrants. The 500 Hz pressure has the more pronounced lobes characteristic of high frequencies. The 33 rpm data, figure 15, show characteristics similar to those of the 26 rpm data.

CONCLUDING REMARKS

Evaluation of the results of this exploratory survey yields an appreciation of the basically low-frequency nature of wind turbine noise. Acoustic levels for this wind turbine are relatively low and at moderate distances - 150 to 180 m (500 - 600 ft) comparable in level to the background wind noise. Infrasonic levels are dominated by background noise although some periodic tones exist.

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2. R. L. Thomas and T. R. Richards, "ERDA/NASA 100-Kilowatt MOD-0 Wind Turbine Operations and Performance," Conference on Wind Energy Conversion Systems, Washington, D.C., Sept. 19-21 (1977), or NASA TM-73825 (1977).

3. D. L. Johnson, "Infrasound, Its Sources and Its Effects on Man," Rep. No. AMRL-TR-76-17, Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Ohio (May 1976). (AD-A032401).

TABLE I - MICROPHONE RESPONSE CORRECTIONS
(LOW FREQUENCY)

Frequency (Hz)	2.5 cm Diameter Microphone M1 Correction (dB)	1.2 cm Diameter Microphone M2 Correction (dB)
0.6	19.0	29.0
0.8	16.0	20.0
1.0	11.5	13.5
1.5	6.0	9.0
2.0	4.0	6.0
3.0	1.8	3.0
4.0	1.0	2.0
6.0	.5	1.5
8.0	.2	1.0
10.0	0	.6
20.0	0	0

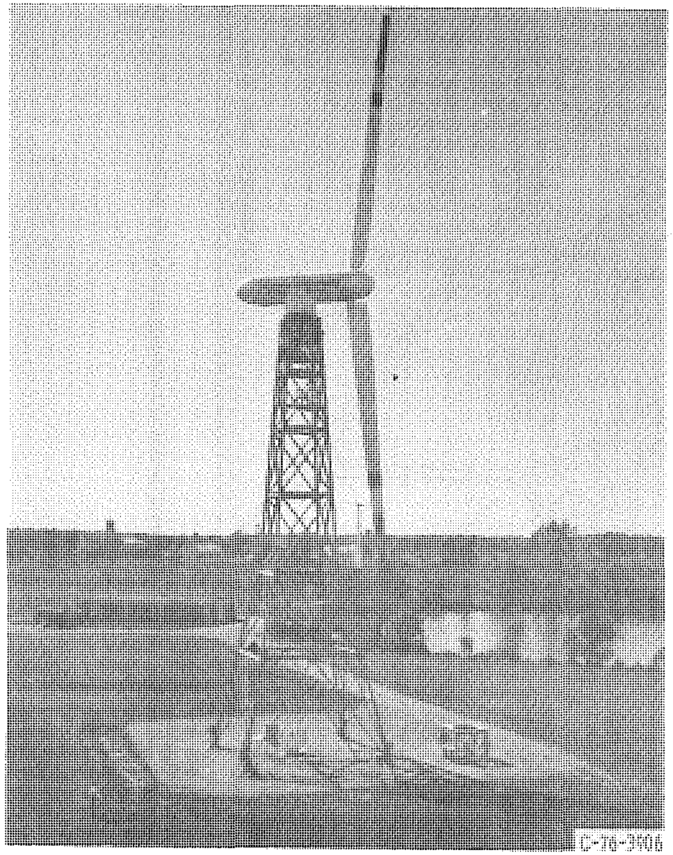

Figure 1. - View of wind turbine with full-span blades.

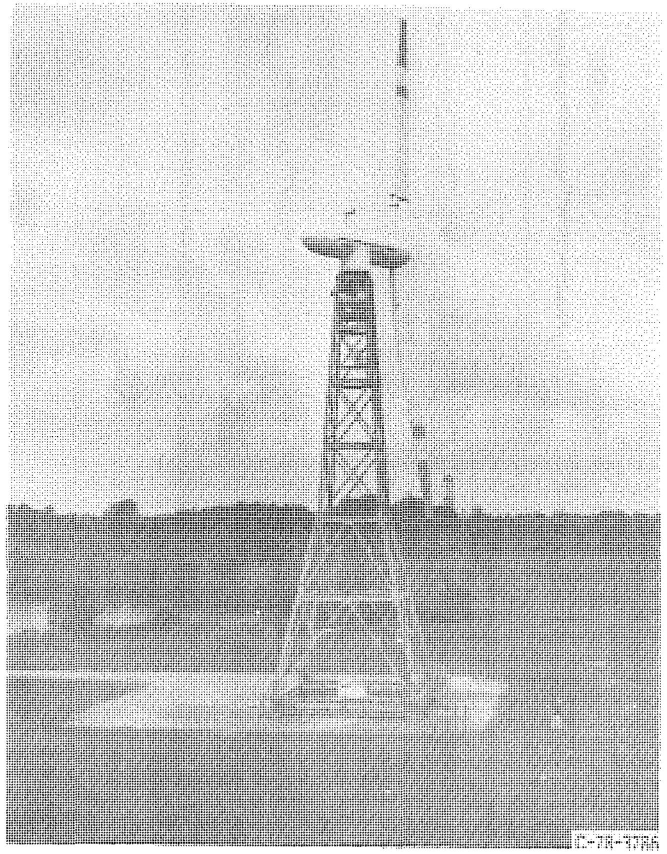

Figure 2. - View of wind turbine with part-span blades.

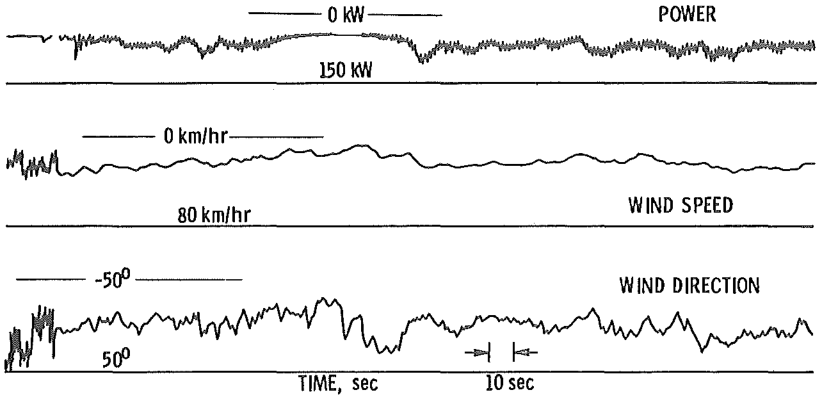

Figure 3. - Wind turbine operating parameters during noise measurements (first test series).

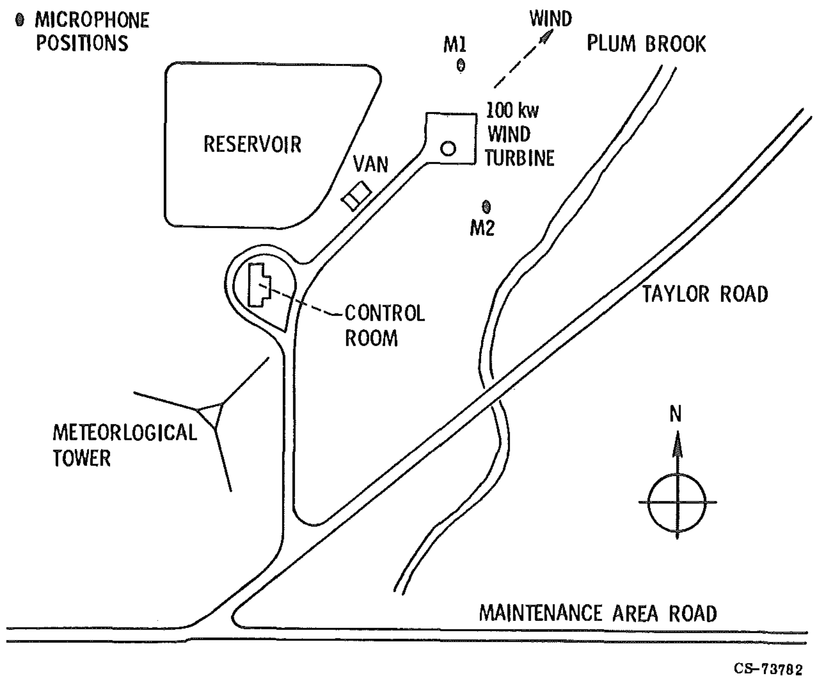

Figure 4. - Plan view of wind turbine site showing microphone locations for first test series.

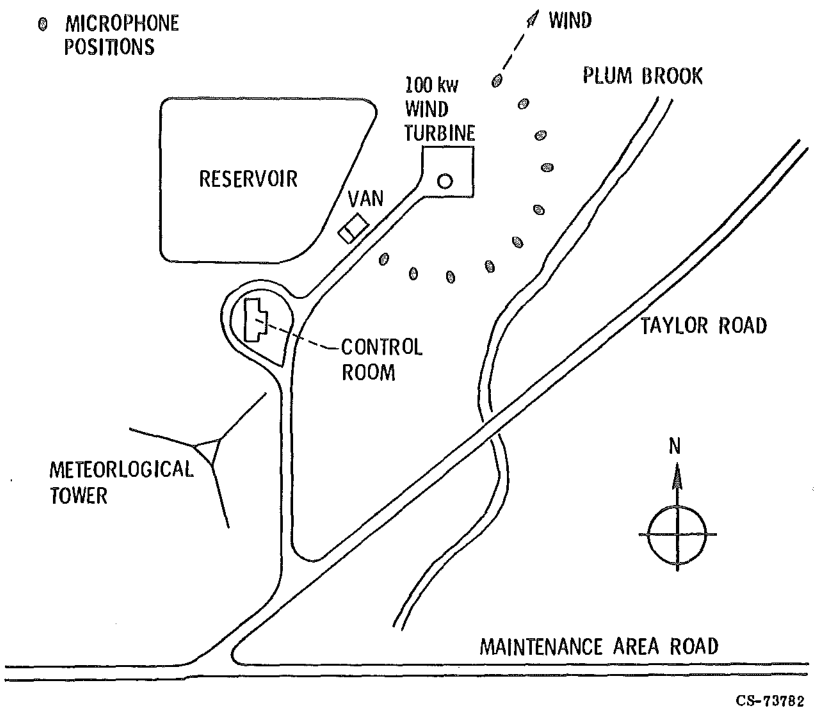

Figure 5. - Plan view of wind turbine site showing microphone locations for second test series.

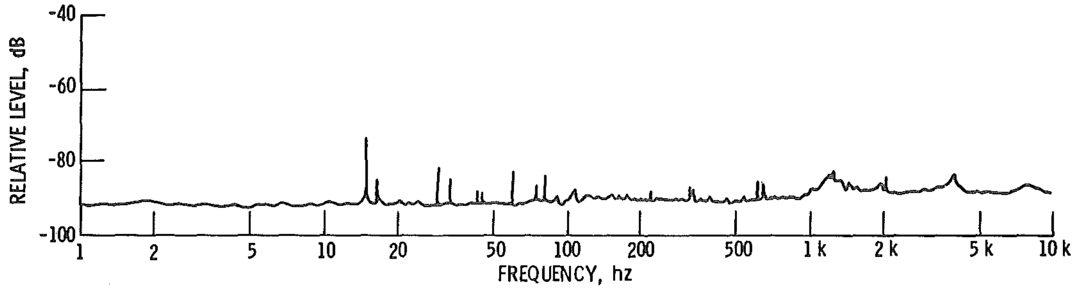

Figure 6. - Tape recorder noise spectrum.

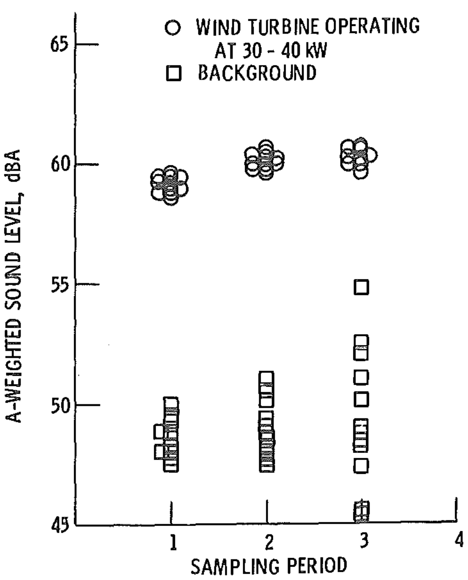

Figure 7. - A-weighted sound levels measured by reference microphone at 200 feet (microphone M2, first series, 30 sec average).

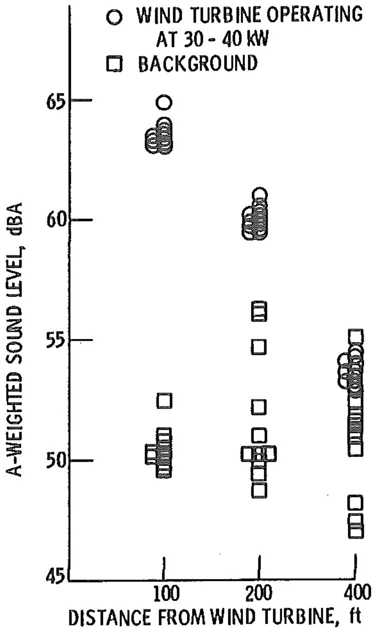

Figure 8. - A-weighted sound levels as a function of distance from wind turbine (microphone M1, first series, 30 sec average).

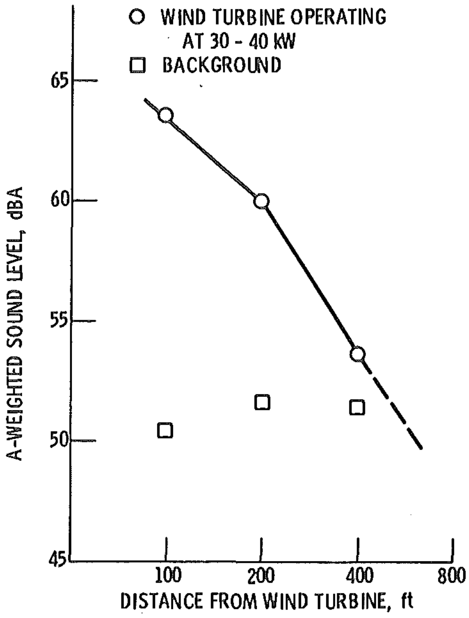

Figure 9. - A-weighted average sound levels as a function of distance from wind turbine (microphone M1, first series, 6 min. average).

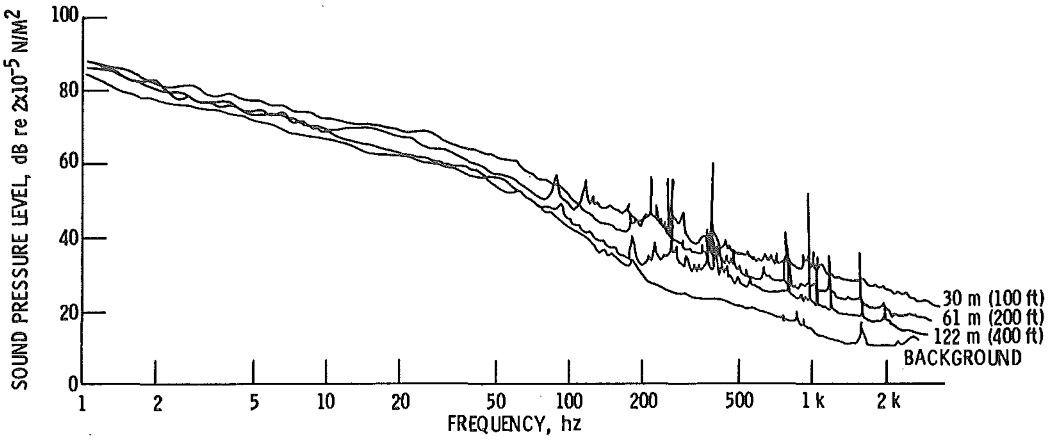

Figure 10. - Wind turbine sound pressure level spectra (1 hz bandwidth, first test series, 40 rpm).

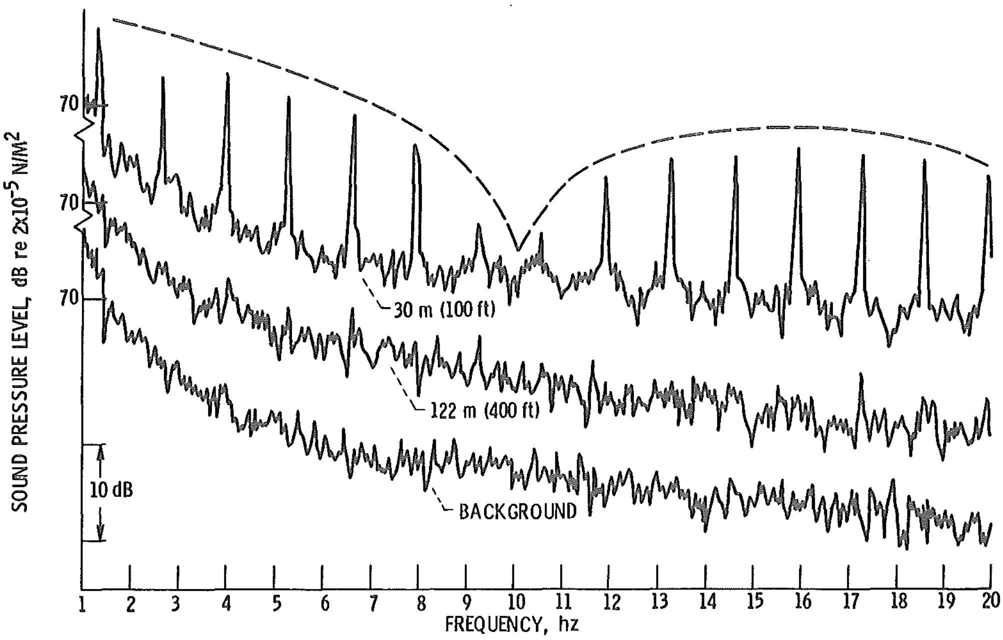

Figure 11. - Wind turbine sound levels at 30 m (100 ft) and 122 m (400 ft) at 40 rpm and background level (0.03 hz bandwidth).

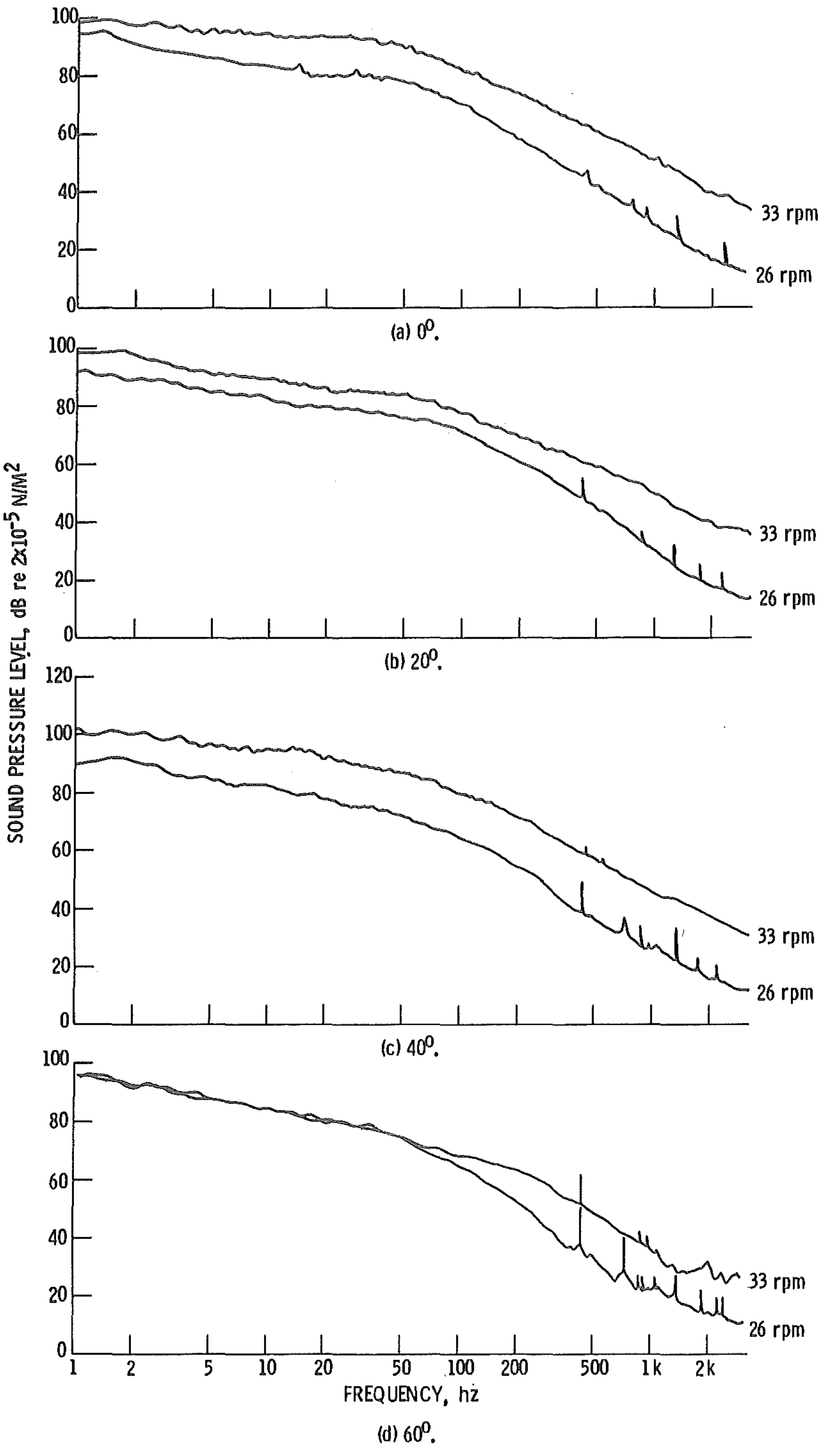

Figure 12. - Wind turbine sound pressure level (SPL) at 61 m (200 ft) locations (1 hz bandwidth).

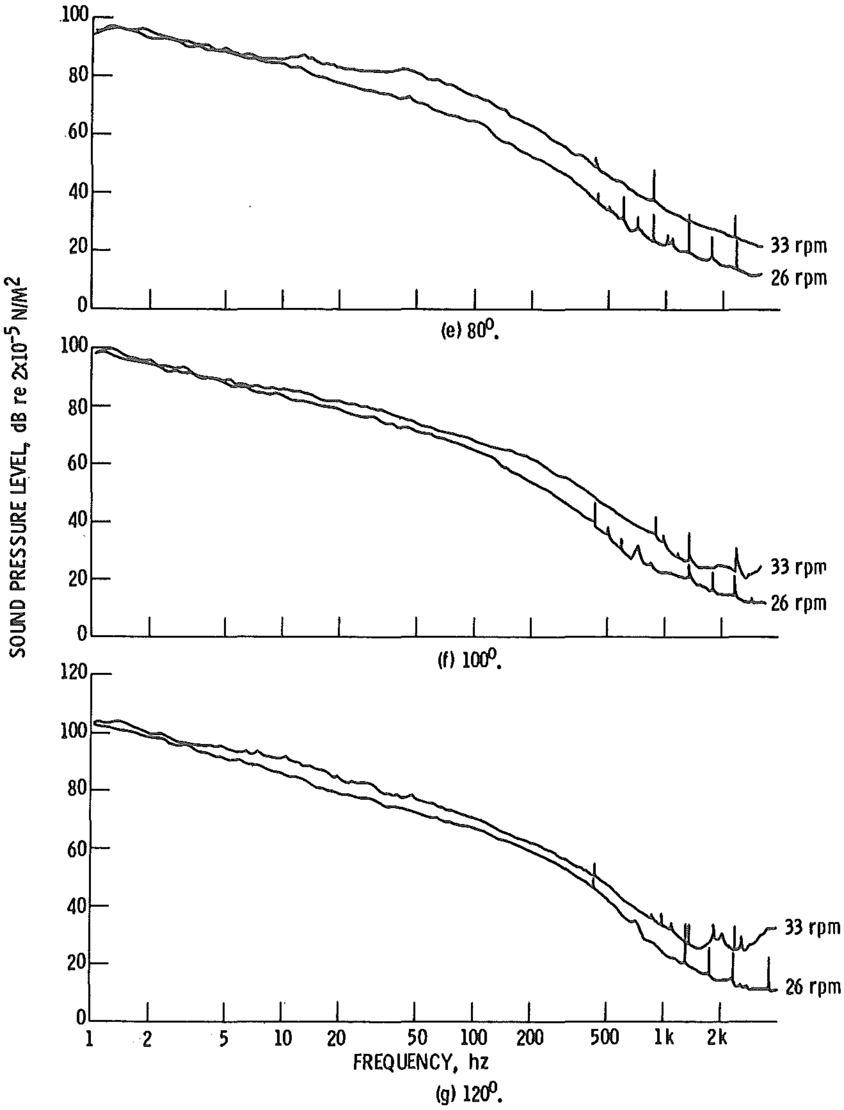

Figure 12. - Continued.

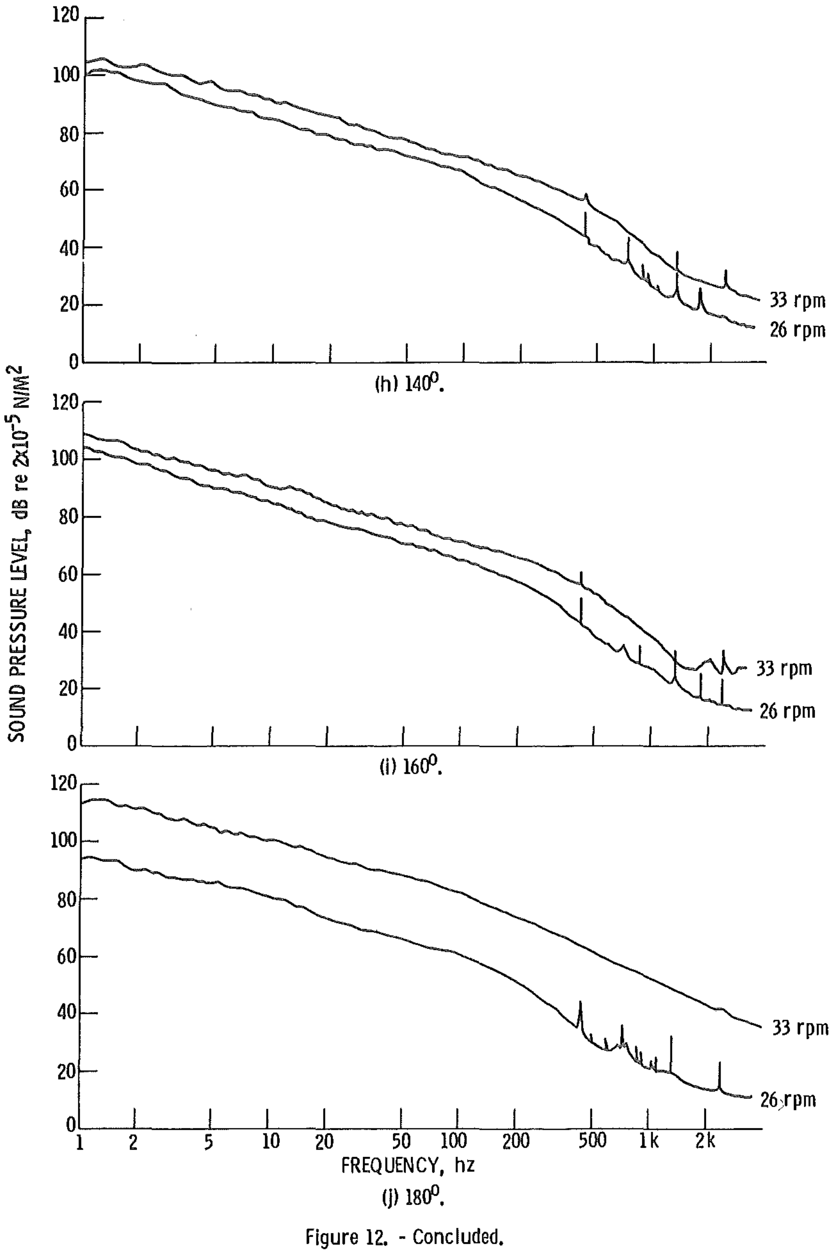

Figure 12. - Concluded.

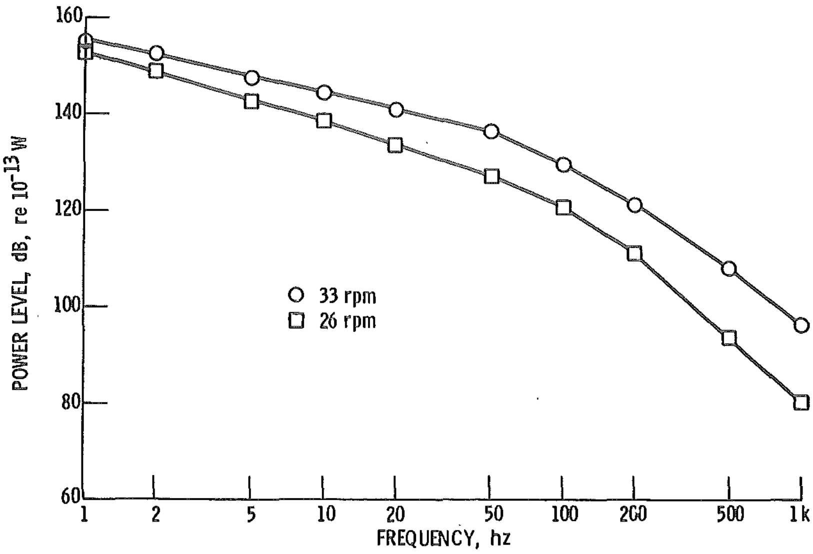

Figure 13. - Wind turbine sound power level at two speeds.

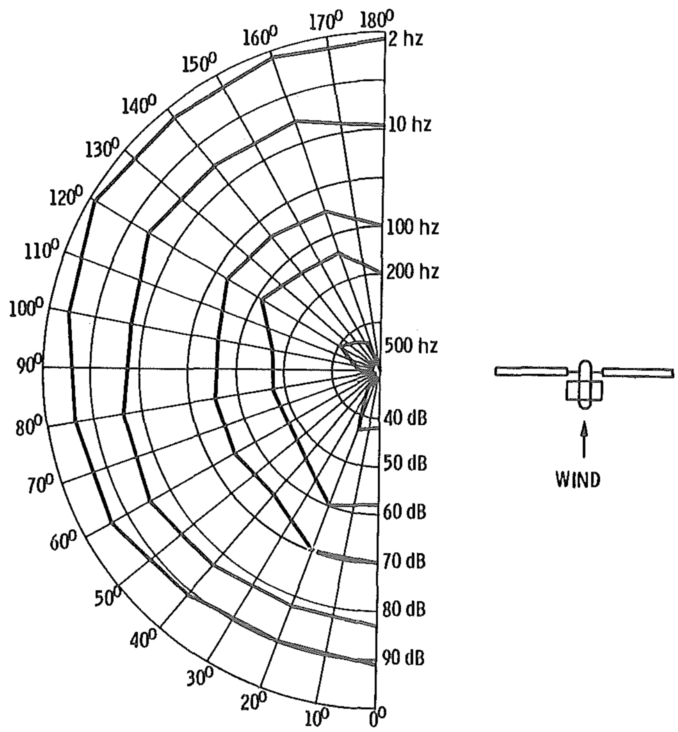

Figure 14. - Wind turbine noise directivity at 26 rpm.

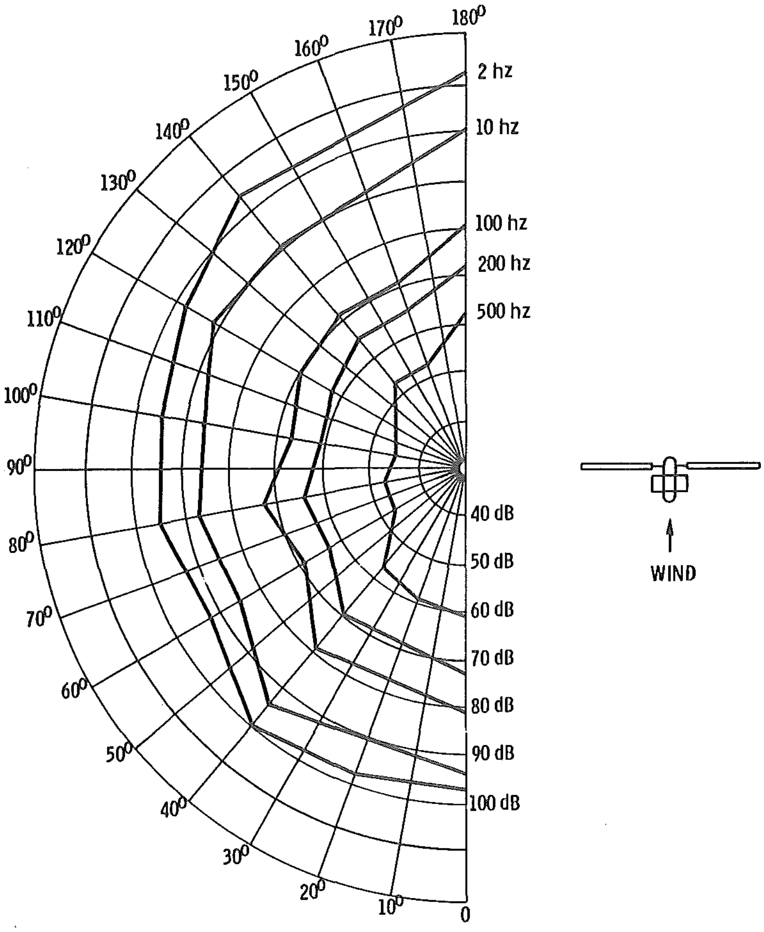

Figure 15. - Wind turbine noise directivity at 33 rpm.

1. Report No. NASA TM-81486	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle AN EXPLORATORY SURVEY OF NOISE LEVELS ASSOCIATED WITH A 100 kW WIND TURBINE		5. Report Date
		6. Performing Organization Code
7. Author(s) J. R. Balombin		8. Performing Organization Report No. E-424
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Ninety-ninth Meeting of the Acoustical Society of America, Atlanta, Georgia, April 21-25, 1980.

16. Abstract

During performance tests of a 125-foot diameter, 100 kW wind turbine at the NASA Plum Brook Station near Sandusky, Ohio, the opportunity arose to make exploratory noise measurements and results of those surveys are presented. The data include measurements as functions of distance from the turbine, and directivity angle, and cover a frequency range from 1 Hz to several kHz. Potential community impact is discussed in terms of A-weighted noise levels relative to background levels, and the infrasonic spectral content. Finally, the change in the sound power spectrum associated with a change in the rotor speed is described. The acoustic impact of this size wind turbine is judged to be minimal.

17. Key Words (Suggested by Author(s)) Wind turbine; Noise level	18. Distribution Statement Unclassified - unlimited; STAR Category 71

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

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Appendix

Summary - Presentation

at MBB-Munich, September 25

GROWIAN II PROGRAM OVERVIEW

- PROGRAM OBJECTIVES

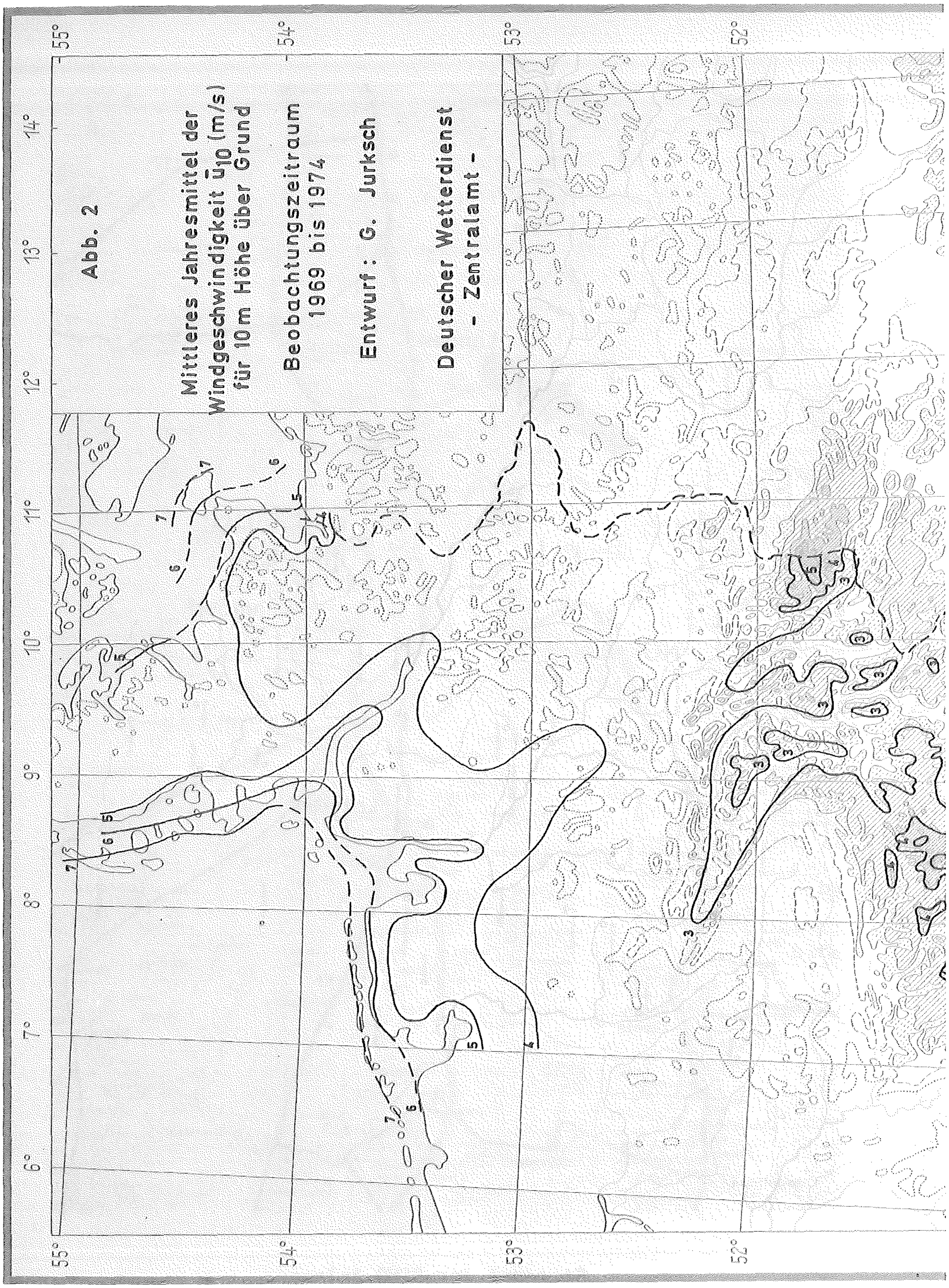
  - INVESTIGATION OF ADVANCED CONCEPTS FOR LARGE WECS IN THE POWER CLASS OF $\geq$ 5 MW_{EL} OR ROTOR DIAMETERS OF $\geq$ 135 M

  - MANUFACTURING AND ASSEMBLY DOCUMENTATION FOR 1 : 1 - WECS

  - DESIGN, MFG, ASSY AND TEST OF A SCALED DEMONSTRATOR SYSTEM WITH MAJOR SIMILARITIES (AERODYNAMICS, ELASTIC PROPERTIES, AEROELASTIC PROPERTIES)

- MILESTONES

∘ PROGRAM START:	7/78
∘ CONCEPT SELECTION:	3/79
∘ DEMONSTRATOR MFG & ASSY DOCUMENTATION:	10/80
∘ DEMONSTRATOR ASSEMBLY	6/81
∘ PREL. TEST DATA EVALUATION; DESIGN FREEZE FOR 1 : 1 - WECS DOCS.	10/81
∘ 1 : 1 - WECS DOCUMENTATION; CONTRACT CONCLUSION	12/81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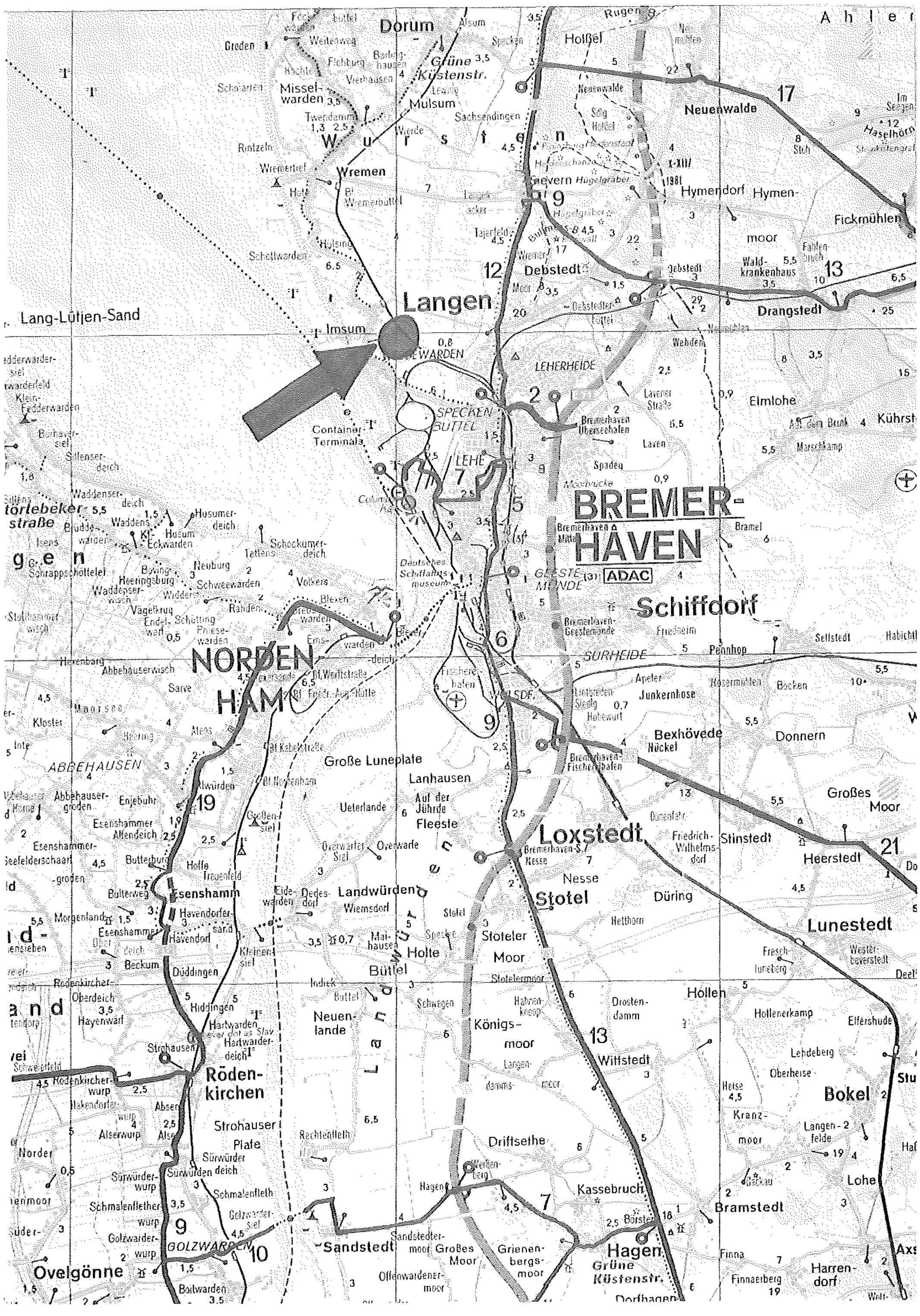
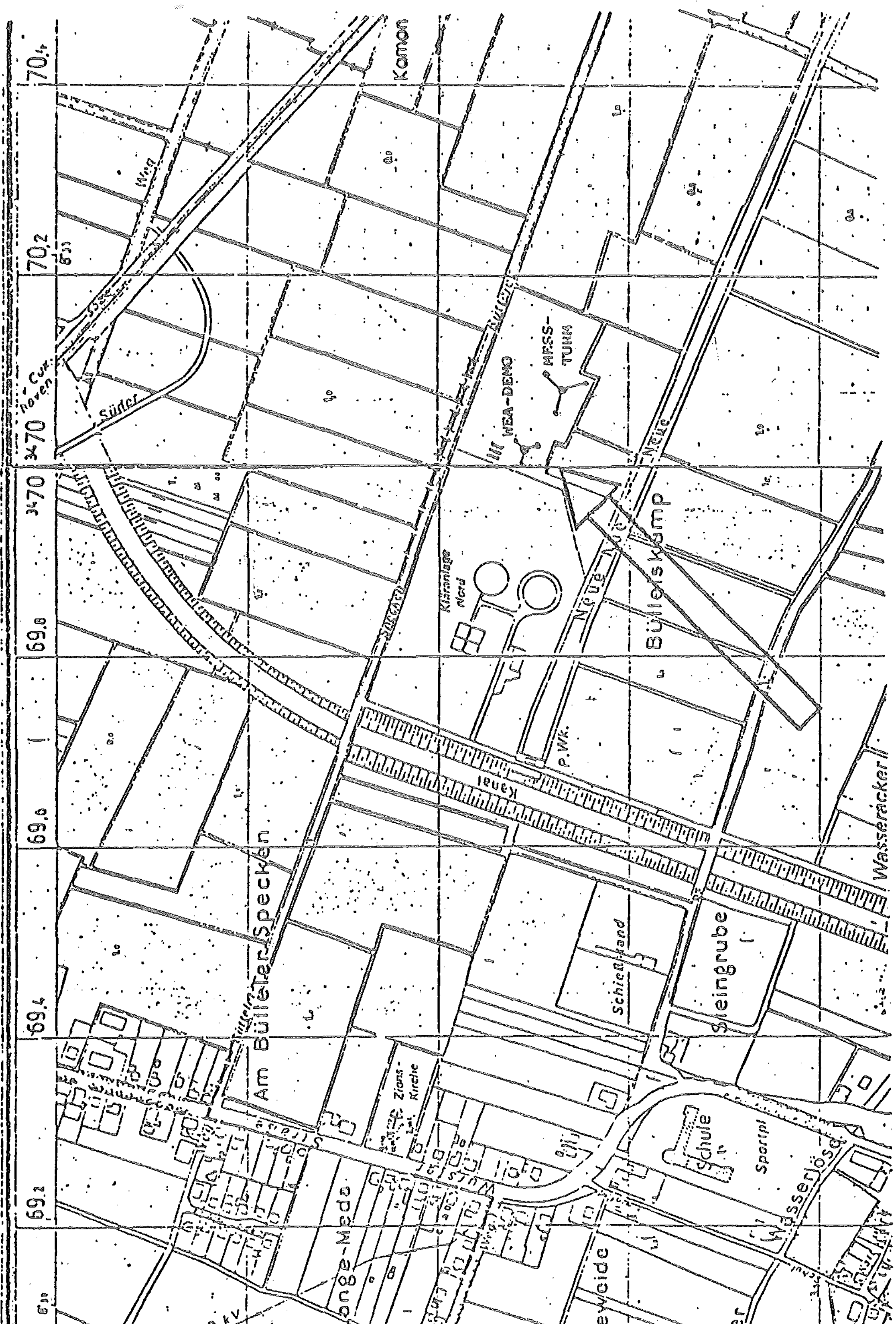
Mittleres Jahresmittel der Windgeschwindigkeit $\bar{u}_{10}$ (m/s) für 10 m Höhe über Grund
Beobachtungszeitraum 1969 bis 1974
Entwurf: G. Jurksch
Deutscher Wetterdienst - Zentralamt -



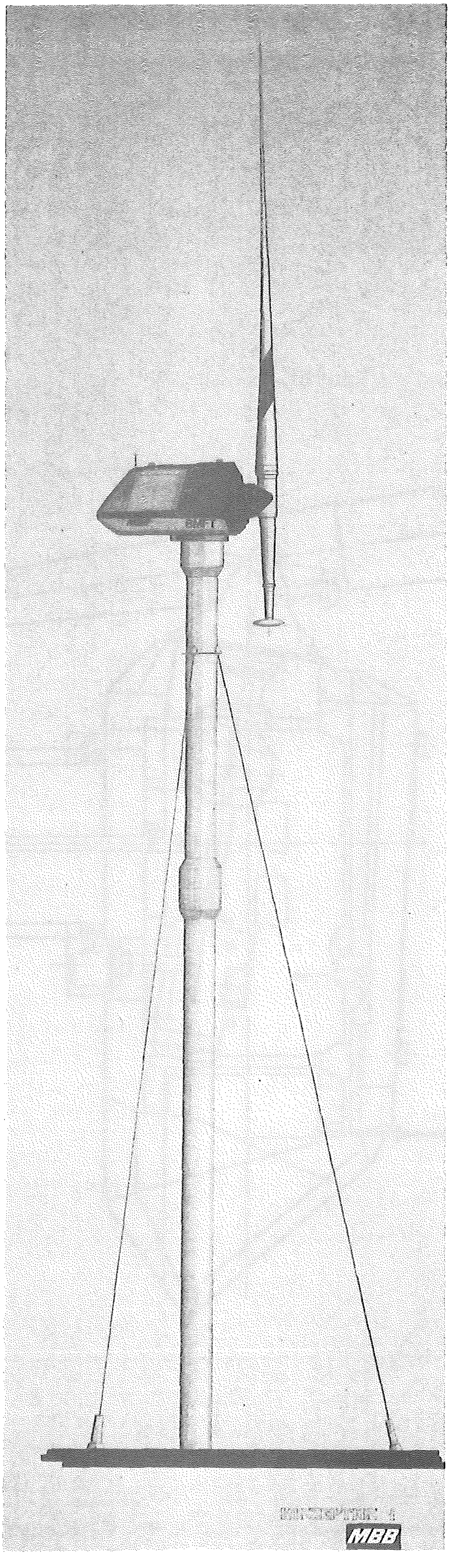
Standort der DEMO-Anlage

Weddewarden
(Stadt Bremerhaven)

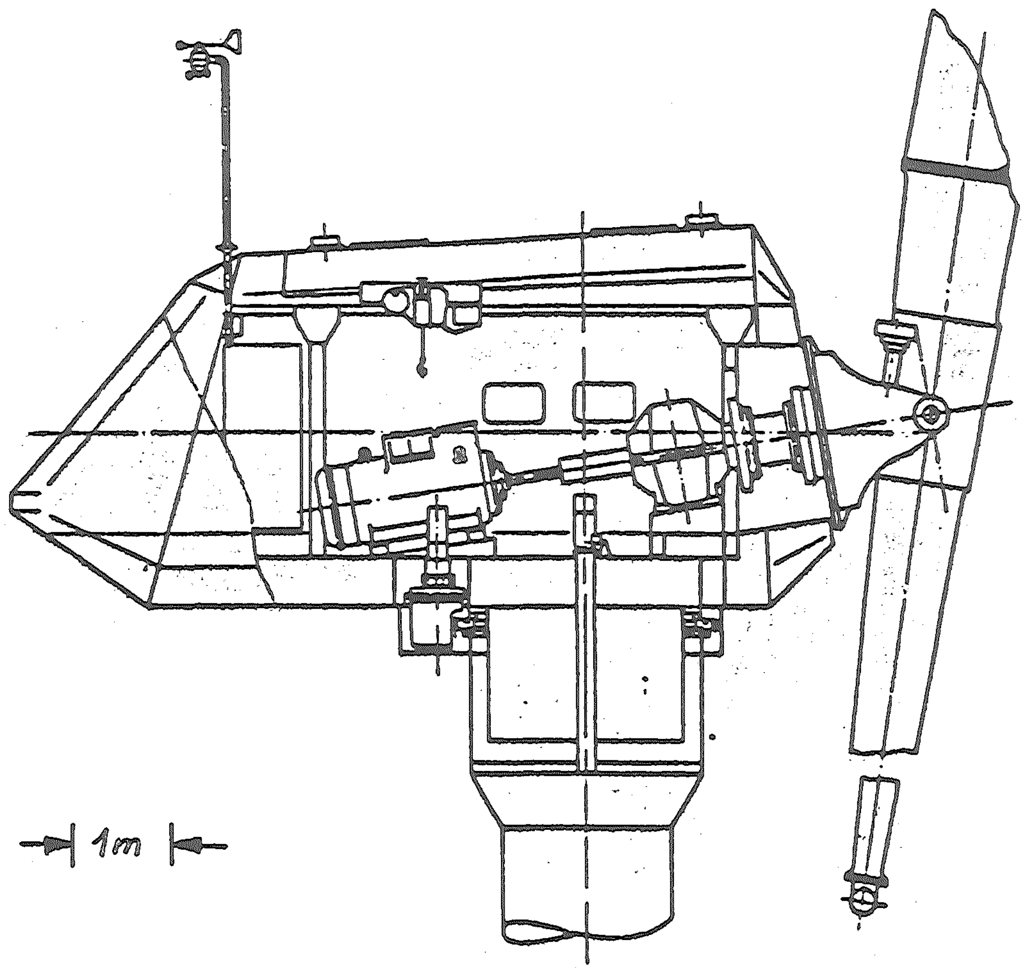


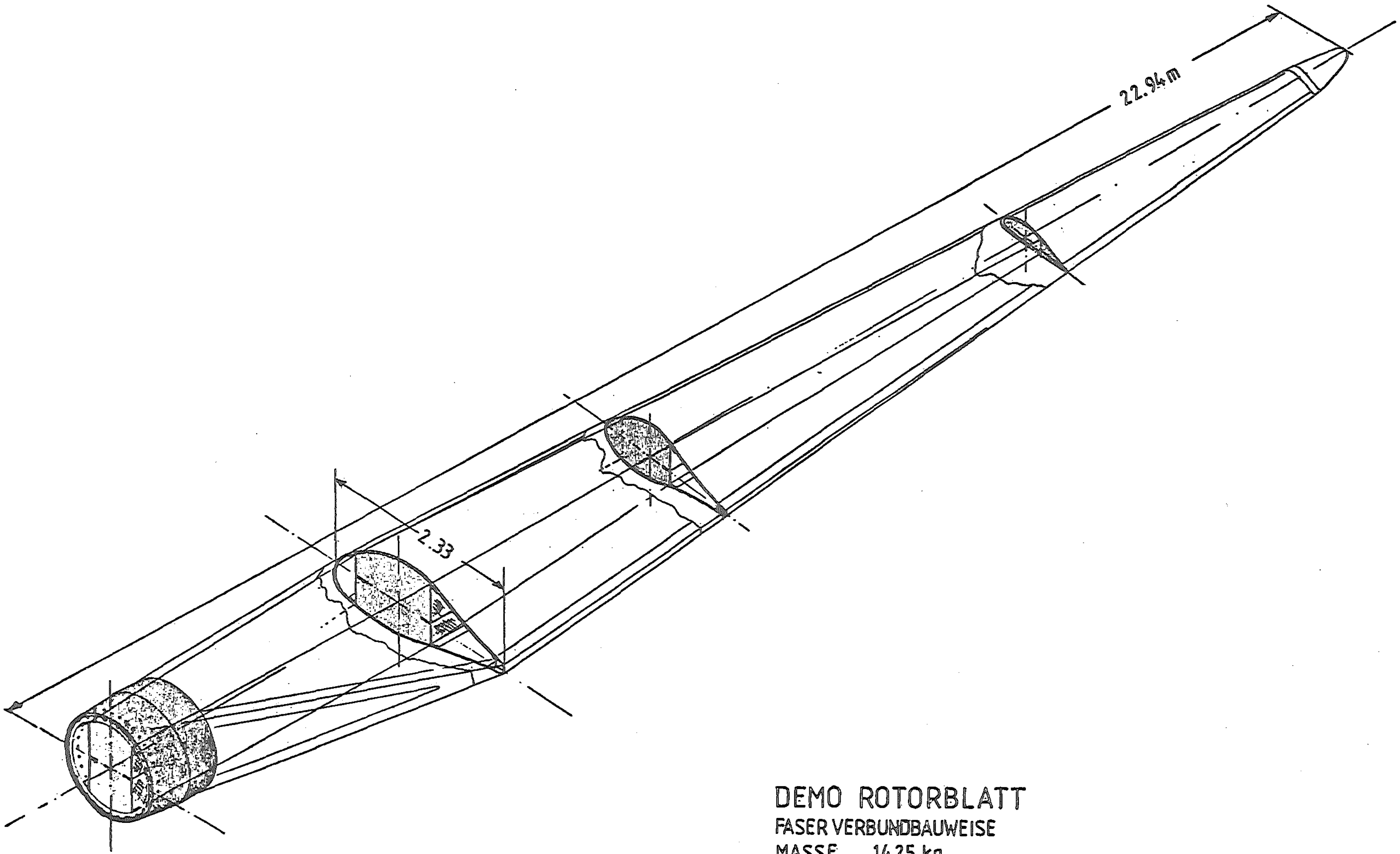
Lageplan der DEMO-Anlage


Windenergieanlage 5MWel

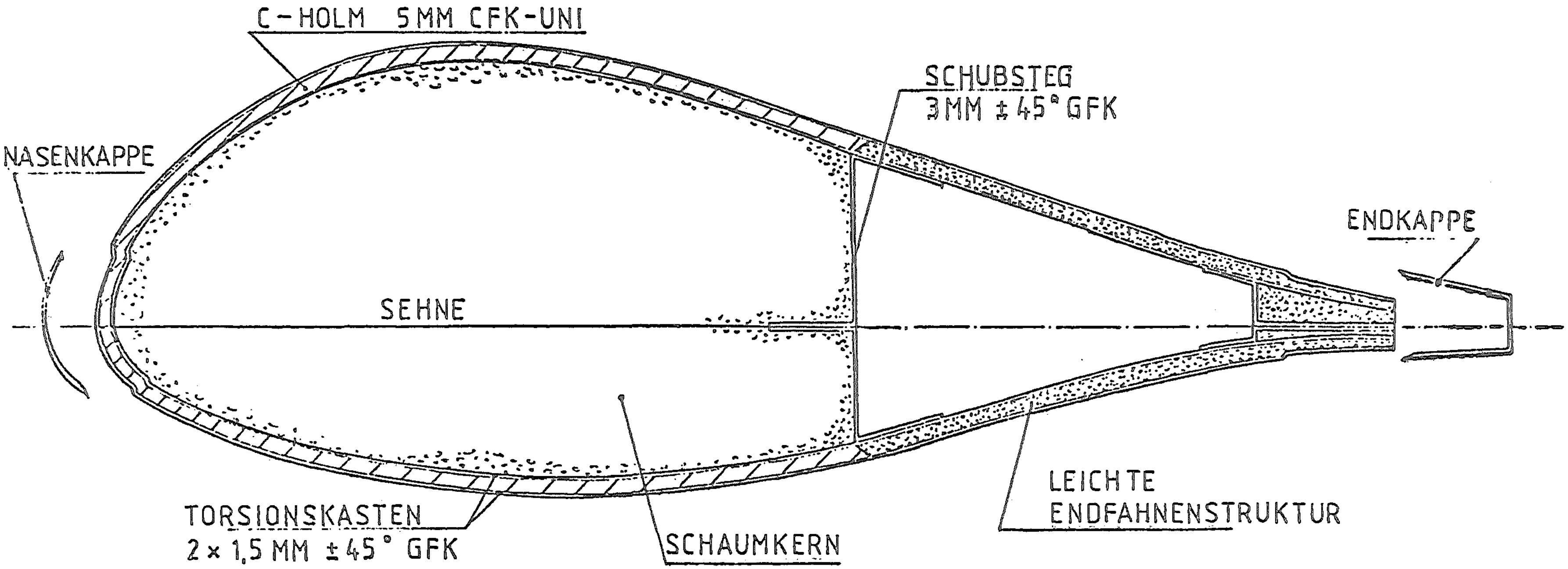

MBB

DEMONSTRATOR NACELLE
INBOARD PROFILE





DEMO ROTORBLATT
FASER VERBUNDBAUWEISE
MASSE 1425 kg
WORTMANN FX – 77 – W PROFILE
CA. 15° VERWINDUNG



Profilquerschnitt Rotorblatt DEMO-Anlage

DESIGN CHARACTERISTICS OF SELECTED CONCEPT

ROTOR:

- ONE-BLADE, DOWNWIND
- TEETERING HUB
- COUNTERBALANCE ARM/WEIGHT
- COMPOSITE ROTOR BLADE
- FULL PITCH CONTROL OF ROTOR BLADE / COUNTERBALANCE SIDE
- PITCH BEARINGS RELIEFED FROM CENTRIFUGAT FORCES
- PITCH ACTUATION BY DC-MOTOR; GEAR BOXES (2), PINIONS (2)
  ACTING ON GEAR RIM; UNIT PRESTRESSED BY BEVEL GEAR-LINK BETWEEN GEAR BOXES

DRIVE TRAIN:

- STIFF LOW-SPEED SHAFT
- CROSSWISE ROLLER BEARING
- 3 STAGE STEP-UP GEAR BOX
- CARDAN HIGH-SPEED SHAFT, DISC BRAKE, SLIPPING CLUTCH
- AUXILIARY DRIVE FOR ROTOR POSITIONING

CONTINUED

CONTROL CONCEPT:

- VARIABLE SPEED CONCEPT: $\pm$ 10 PER CENT ABOUT SYNCHRONOUS
- SPEED-DEPENDANT ACTIVE POWER CONTROL
- CONSTANT PITCH ANGLE BELOW RATED POWER / CONSTANT TIP SPEED RATIO BY SPEED VARIATION $\Longrightarrow$ C_{PMAX} CONTROL
- THRESHOLD CONTROL OF POWER AND SPEED VIA PITCH CONTROL UNIT
- ACTIVE AZIMUTH CONTROL

OVERALL SYSTEM CONTROL:

- INTEGRATED SYSTEM WITH CENTRALIZED AND DEDICATED UNITS
- BOTH MANUAL (SEMI-AUTOMATIC) AND AUTOMATIC CONTROL FROM CONTROL CENTER AND NACELLE (SERVICE MODE ONLY)
- SOPHISTICATED SIGNAL AND COMMAND HIERARCHY
- AT LEAST FAIL-SAFE CAPABILITY

CONTINUED

AZIMUTH DRIVE:

- REDUNDANT DRIVE UNIT SIMILAR TO PITCH ACTUATOR

TOWER:

- SOFT TOWER CONCEPT
- VERTICAL TOWER WITH CYLINDRICAL CROSS SECTION
- STEEL (DEMONSTRATOR) OR CONCRETE TOWER
- 3 SUPPORT CABLES
- FRANKI PILE/CONCRETE FOUNDATION
- TRIM MASS FOR 2ND BENDING FREQUENCY
- ELEVATOR

POWER GENERATION:

- AC/DC/AC SYSTEM: SYNCHROUNUS GENERATOR / DC-RECTIFIER SYSTEM / STATIC FREQUENCY CONVERTER
- ALTERNATIVELY: EXCITATION-CONTROLLED ASYNCHRONOUS SYSTEM

TECHNICAL AND PERFORMANCE DATA

		DEMONSTRATOR	1:1-SYSTEM
NUMBER OF BLADES	(-)	1	1
ROTOR DISC DIAMETER	(M)	48,33	145
HUB HEIGHT	(M)	50	120
ACTIVE POWER AT RATED WIND SPEED	(KW_{EL})	370	5000
POWER DENSITY	(W_{EL}/M^2)	200	300
RATED INPUT POWER	(KW)	400	5490
RATED WIND SPEED	(M/SEC)	10	11,5
OPERATIONAL WIND SPEED RANGE	(M/SEC)	5,7 - 16	6,6 - 18
ANNUAL POWER PRODUCTION	(GWH/A)	$>$1,3	$>$17
STATIC ROTATIONAL SPEED RANGE (W.R.T. SYNCHRONOUS SPEED)	(RAD/SEC)	4,6 $\pm$ 0,46	1,8 $\pm$ 0,18
BLADE TIP SPEED AT RATED WIND SPEED	(M/SEC)	120	138
TIP SPEED RATIO AT RATED WIND SPEED	(-)	12	12
MAXIMUM OVERALL POWER COEFFICIENT	(-)	0,37	0,37
AIR FOILS	(-)	WORTMANN FX77-W-SERIES	

CONTINUED

		DEMONSTRATOR	1:1-SYSTEM
MAX./MIN. CHORD LENGHT	(M)	2,33 / 0,56	7 / 1,68
SOLIDITY	(-)	0,0155	0,0155
TWIST, ROOT TO TIP, NONLINEAR	(DEG)	15	15
INCLINATION OF ROTOR AXIS	(DEG)	9	9
MASSES (EXCLUSIVE TOWER, FOUNDATION ETC.):			
° ROTOR TOTAL	(KG)	5910	APPR. 100.000
° ROTOR BLADE	(KG)	1425	" 26.000
° NACELLE, FULLY EQUIPPED	(KG)	28000	" 300.000

WHY ONE-BLADED SYSTEMS ?

PROS:

- LARGE INHERENT BLADE STIFFNESSES BY ENLARGED BLADE CROSS SECTION
  → COMPATIBILITY WITH EIGENFREQUENCY REQUIREMENTS FOR:
  - VARIOUS BLADE TECHNOLOGIES (STEEL, CFK, GFK)
  - EVEN LARGER ROTOR DIAMETERS (GROWTH POTENTIAL)
- LOW TOLERANCE REQUIREMENTS FOR BLADE MANUFACTURING: NO SYMMETRY REQUIREMENTS; BALANCING BY COUNTER WEIGHT ADJUSTMENT
- SIMPLE ROTOR HEAD: SINGLE PITCH CONTROL; PITCH BEARINGS RELIEFED FROM CENTRIFUGAL LOADS
- ONLY 1 MAJOR EXCITATION FRQUENCY: 1/REV (COMPARED TO 1/REV AND 2/REV FOR TWO-BLADED-SYSTEMS):
  → LOWER PARAMETER SENSITIVITY FOR DESIGN AND OPERATION (E.G. TOWER/CABLE EIGEN-FREQUENCIES, ROTATIONAL SPEED RANGE)
- REDUCED COST FOR ROTOR MANUFACTURING & ASSEMBLY

CONS:

- SLIGHTLY REDUCED AERODYNAMIC EFFICIENCY COMPARED TO TWO-BLADED SYSTEMS
- RESIDUAL (AERODYNAMIC) UNBALANCES

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